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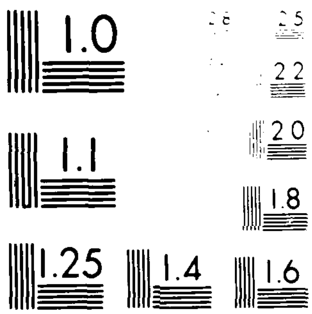
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TRESTLE PULSER IMPROVEMENT STUDY

Mission Research Corporation
1400 San Mateo Blvd, SE
Albuquerque, NM 87108

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November 1981

Final Report

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report documents theoretical efforts undertaken to determine the engineering feasibility of design modifications suggested for the purpose of improving the performance of the existing pulse generator system used in the TRESTLE facility. A test plan is outlined for the evaluation of these modifications, and approximate costs are given for the modifications.

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PREFACE

The authors would like to acknowledge the contributions of the individuals who participated in this study and were a source of many of its conclusions: John Shannon, Maxwell Laboratories, Inc.; J. T. Naff, Physics International Company; Walter Crewson, Pulsar Products, Inc.; and Ian Smith, Pulse Sciences, Inc.

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I. INTRODUCTION

This report documents theoretical efforts undertaken to determine the engineering feasibility of design modifications suggested for the purpose of improving the performance of the existing pulse generator system used in the TRESTLE facility.

In performance of the tasks directed under this effort, a number of experts in the field of pulse power technology were consulted and their views on the required experiments and modifications sought. In order to perform this task, the existing data on the TRESTLE system were reviewed, the current state of applicable pulse power technology was reviewed, and the overall design of the TRESTLE was studied. The reports from these consultants are included as appendices to this report.

Since 1974 it has been known that the TRESTLE would have various limitations, and more recent measurements have confirmed these predictions. In order to improve the waveform of the TRESTLE, it will be necessary to make modifications of the pulse power systems and perhaps some portions of the array as well. Numerous theoretical studies have been made to identify the necessary modifications and estimate the degree of improvement possible. Before actually performing the suggested modifications, however, it is important to verify that the changes suggested will accomplish their goals, and also to determine whether these modifications are feasible in terms of the present level of high voltage technology.

In order to select among the proposed modifications, the authors of this report have examined the changes suggested to date, and made an effort to select for further work those which appear most likely to yield the desired results. We have therefore tried to develop an experimental program which will require the minimum time and expense to yield the necessary information for making a decision on the final modifications to the TRESTLE.

II. EVALUATION OF AVAILABLE DATA

Field mapping experiments in the working volume of the ATLAS I (TRESTLE) facility were first performed in September 1979. Although measurements of electromagnetic fields outside the physical confines of the simulator were also made, we focus our attention for the present purposes on the working volume environment available to the facility user. For the purposes of this report, we shall review the working volume fields, while pointing out some salient features and deficiencies.

Figure 1 shows a schematic diagram of the simulator facility in its top and side view. In the top view of the simulator, the working volume, which is a circular cylinder of diameter 75.7 m and height of 20 m, has been identified. Figure 2 shows an enlarged view of the working volume, on which the field mapping test points are also indicated. Note that in this figure the origin of a rectangular coordinate system (x, y, z) is chosen to be the intersection of the center line (z axis) and the working volume, on the pulser end. The center line is about 5 m above the platform. In this coordinate system, a planar TEM wave has its principal field components in E_x and B_y. One immediately recognizes that any significant presence of E_z and B_z result respectively in the undesirable TM_{On} and TE_{Om} modes. We shall also be reviewing all available data on these undesirable axial components of electric and magnetic fields. Returning to the principal components E_x and B_y, the coordinates of the test points where they are measured are indicated in Figure 2, in meters. For a detailed documentation and description of nearly all of the experimentally measured fields, the reader is referred to References [1, 2, 3, 4]. The object here is to show some representative fields and indicate the observable features and deficiencies.

The character of the working volume environment is governed strongly by the nature of the individual pulser output. The relevant parameters of pulser output are prepulse, rise time, peak amplitude, notch after the peak, effective decay time, asynchronism, and spectral content. All of these aspects of pulser output significantly impact the quality of environment simulated. With these factors in mind, let us examine the time domain electric, E_x, and magnetic, H_y, fields [2]. They are indicative of the axial and ransvers ariations of the fields within the

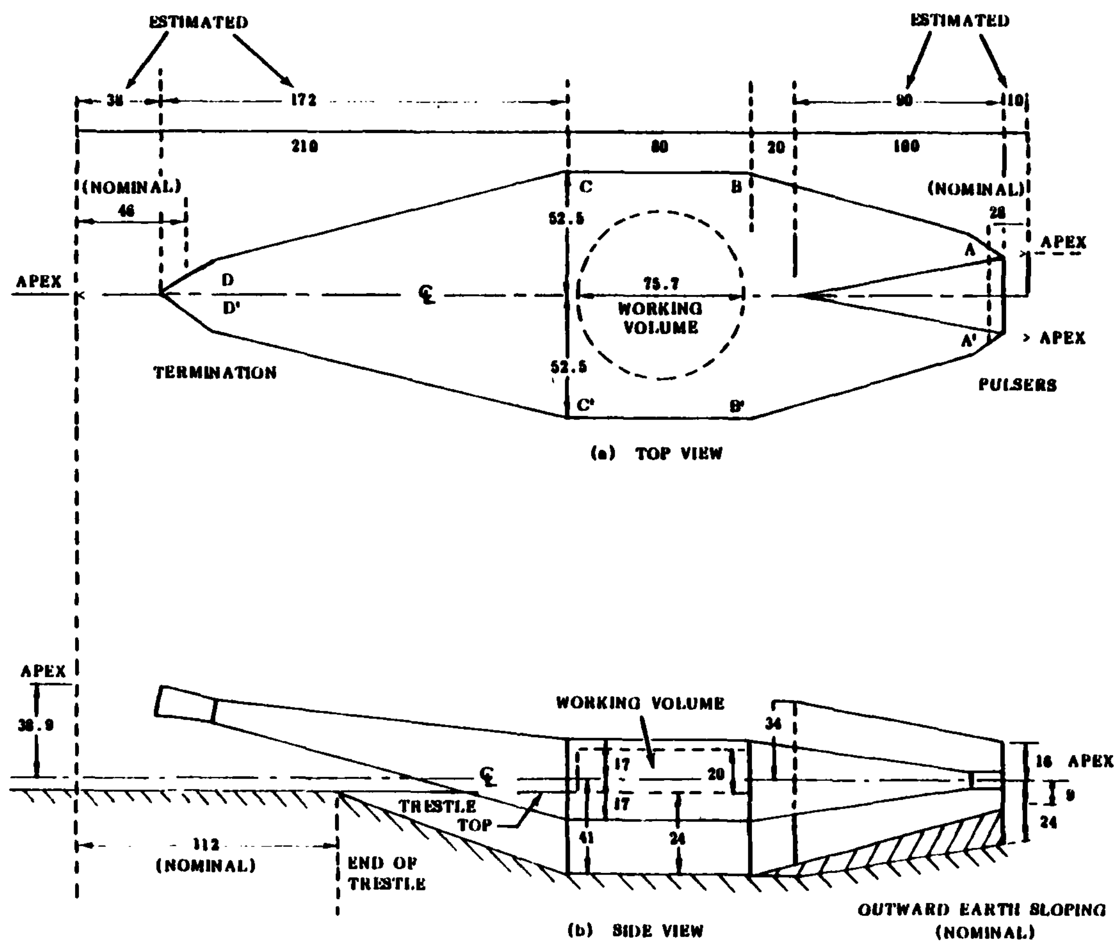


Figure 1. Line schematic diagram of Atlas 1 (TRESTLE) dimensions in meters.

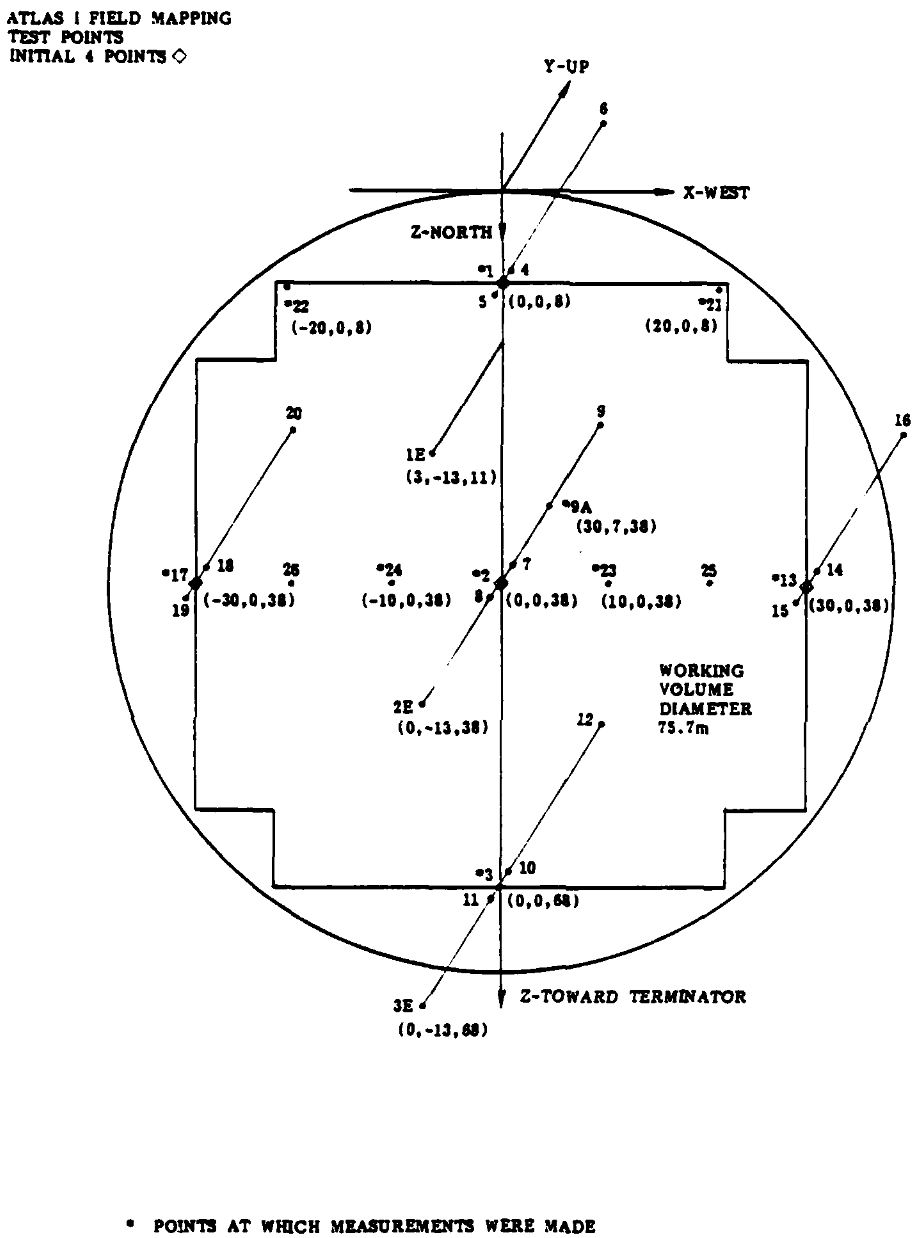


Figure 2. Atlas 1 field mapping test points.

working volume. It is observed that the initial peak falls off about 20% in going from the front to the back of the platform. It is also noted that the late time fields (low frequencies) display little variation in various regions of the working volume. At late times, the electromagnetic fields asymptotically approach the TEM fields. Once again, the striking features of the fields are prepulse and notch after the peak, which both vary over the working volume as the pulse propagates. The measured wave impedance is about 15% less than the nominal value of 377 Ω. In Figure 3, the spectral content of the principal magnetic field at test points 1, 2, and 3 is shown. There is an observable notch in the spectrum, in the range of 1 to 4 MHz, which can be related directly to the pulser output waveform. At frequencies above 10 MHz, the frequency content drops with distance, an effect of pulser asynchronism, wooden platform, ground reflections, etc. Also, the fastest rise rate is observed at the front of the working volume, and the spectral content above 30 MHz is down in the noise.

Figure 4 contains the measured axial magnetic field, H_z, at test points 1, 2, and 3. As was pointed out earlier, this indicates the presence of undesirable TE_{Om} modes. The peak H_z is seen to be about 15 to 20% of the peak H_y, indicating the need for selective non-TEM mode suppression to improve the quality of environment simulated. It is expected that a similar measurement of the axial electric field, E_z, would indicate the presence and the need for suppression of TM_{On} modes. This completes a brief look at the available experimental data from the cited references [1 to 4], from which these figures have been reproduced for review.

In contrast to the data available on the waveforms in the TRESTLE transmission line, the data available on the TRESTLE pulsers are scanty. Only two sensors are in a position to yield diagnostic information from within the pulser itself; an EG&G HSD-3 sensor located on the ground plane 1.07 m from the centerline of the main switch toward the working volume, and a $CuSO_4$ resistive divider across the main switch itself. Thus the HSD-3 probe responds to the fields due to the voltage impressed upon the monocone electrode end of the main switch, while the resistive probe delivers a signal directly proportional to the actual voltage of that same electrode. As might be expected, the data from the two

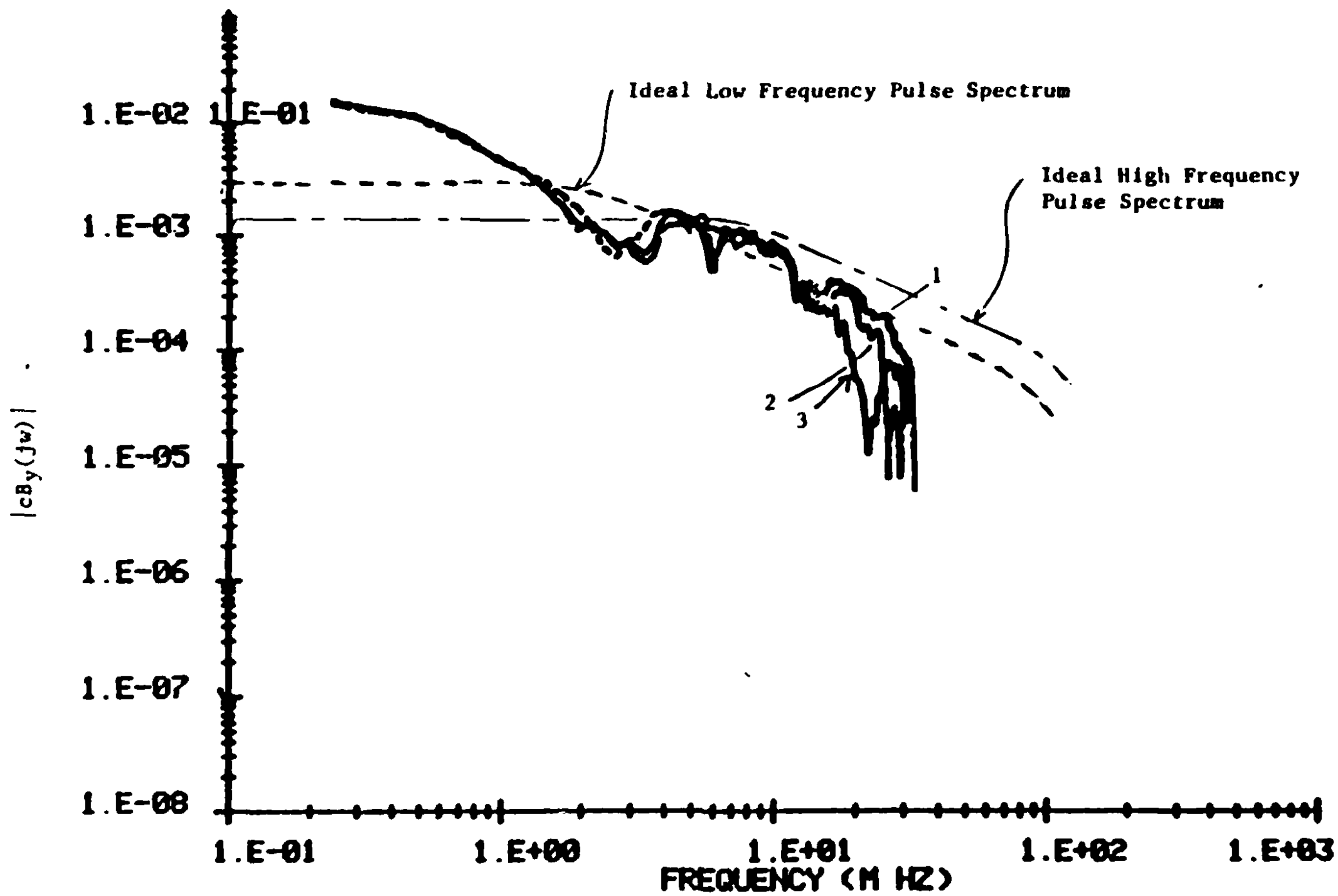


Figure 3. Frequency domain comparison of cBy (jω) fields at test points 1, 2, and 3.

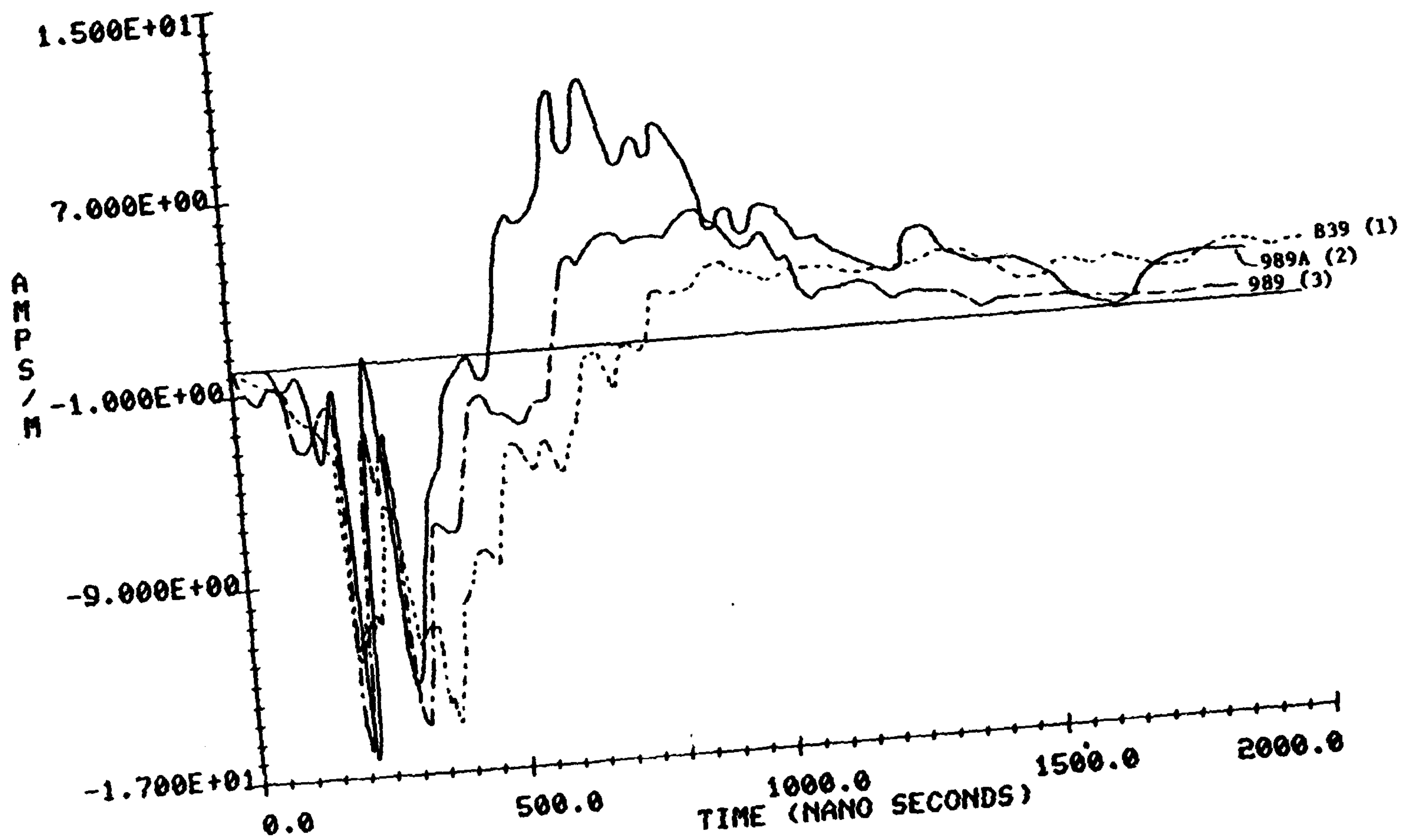


Figure 4. Overlay of H_z at test points 1, 2, and 3.

sensors are generally in excellent agreement. Typical waveforms from these two sensors may be seen in Figures 5A and 5B.

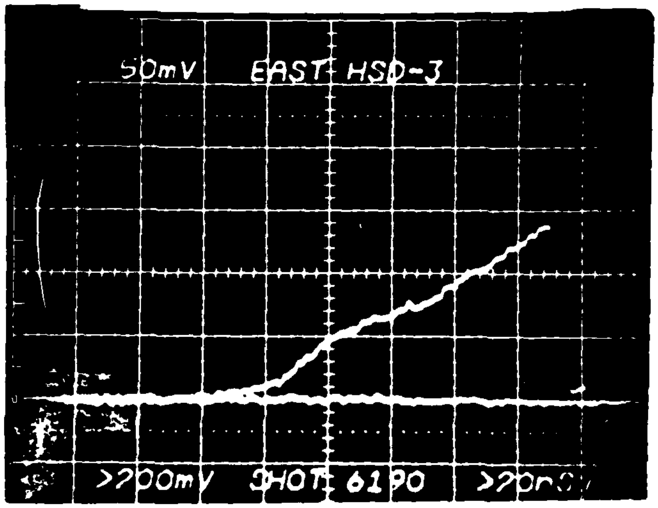
These two sensors are not used directly for the purpose of determining the voltage on the main switch. Their primary use is to determine the time of firing of the main switch relative to the erection of the Marx generator and the chargeup of the peaking capacitors. As can be seen in Figures 5A and 5B, the rise of voltage on the main switch, and therefore the rise of voltage on the peaking capacitors, can easily be determined with reasonable accuracy, especially after some practice. These data are used to set the main switch gap, and thereby the main switch firing time (also called the firing angle).

All other sensors in place in the TRESTLE during normal operation are much further down toward the working volume. Two field sensors are located 23.77 m from the pulser apex, and two more 97.23 m from the pulser apex. There is one additional sensor projecting outward from the point of the wedge toward the working volume. Data are regularly taken from some or all of these sensors, but these data are not useful in determining any of the pulser parameters except the asynchronism between the two pulsers.

Various suggestions have been made for other pulser diagnostics, but none have yet been implemented. Several of the experiments proposed in this study involve the use of additional pulser diagnostic means.

TRESTLE ENVIRONMENT RECORD

Date	10/20/80
Operator	JHP
Shot No.	6190
Attenuation	X50
Vert. Sens.	/Div.
Sweep Speed	/Div.
Sensor Type	
Charge Level	75KV
Sensor Location	
Integrator Time Constant	1.0 MS
External Trigger Delay	1.105 MS
FIDU Delay	1.05 ms
Comments	



Date	SAME
Operator	
Shot No.	
Attenuation	
Vert. Sens.	/Div.
Sweep Speed	/Div.
Sensor Type	
Charge Level	
Sensor Location	
Integrator Time Constant	
External Trigger Delay	
FIDU Delay	
Comments	

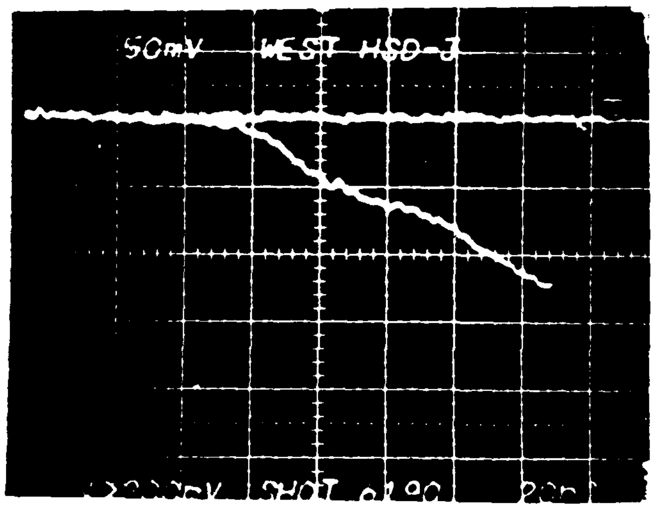
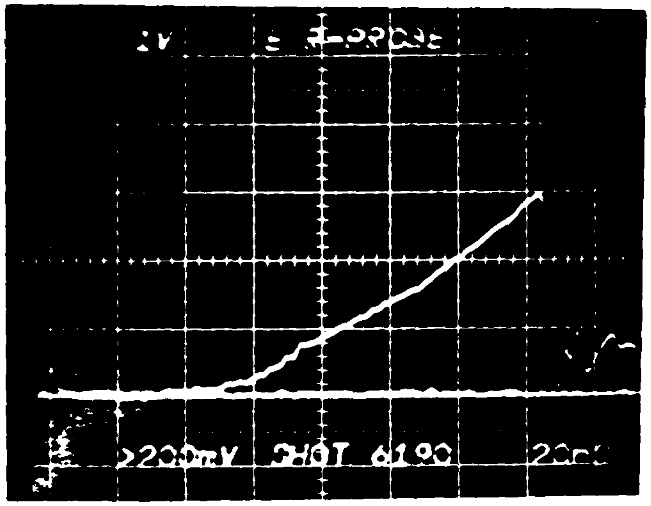


Figure 5a. HSD-3 waveforms.

TRESTLE ENVIRONMENT RECORD

Date	10/20/80
Operator	[illegible]
Shot No.	6190
Attenuation	500
Vert. Sens.	/Div.
Sweep Speed	/Div.
Sensor Type	
Charge Level	75KV
Sensor Location	
Integrator Time Constant	none
External Trigger Delay	1.105 ms
FIDU Delay	1.05 ms
Comments	



Date	
Operator	
Shot No.	SAME
Attenuation	
Vert. Sens.	/Div.
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Sensor Type	
Charge Level	
Sensor Location	
Integrator Time Constant	
External Trigger Delay	
FIDU Delay	
Comments	

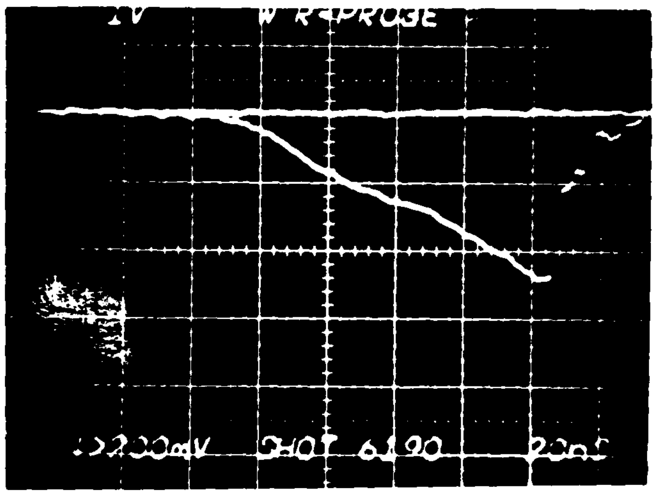


Figure 5b. Resistive probe waveforms.

III. TRESTLE PULSER DESIGN REVIEW

1. OUTPUT SWITCH

Reference [5], by one of the authors of this report, included a physical description of the monocone output switch as configured in ATLAS I. Figures A2 and A3 (on pages 47 and 48) depict the main switch and its arrangement in the TRESTLE pulser. The arrangement of the peakers, switch, Marx and gas box may also be seen in these figures. This report also addressed some methods of improving the impedance matching of the switch with the remainder of the pulser. Since the objective here is to suggest improvements, the two recommended modifications from Reference [5] are reproduced below for consideration.

a. Change of the half cone angle β--When the change was made in 1974 from the bicone to the monocone switch configuration, it was decided to continue using the same switch housing. This switch housing, however, consists of a steel dome, whereas the housing itself is made of fiberglass. Since the dome is metallic, it had to be of a certain minimum diameter to support the field levels. This minimum diameter leads one to the 20° value for the half cone angle, thus resulting in a smaller characteristic impedance value than desirable. Serious consideration should be given to fabricating a new switch housing using a fiberglass dome. Such a housing would permit a cone half angle of about 10°, which would yield the desired impedance.

b. Ground plane variations--The switch cone, with its axis normal to the ground plane wedge, makes a sharp angle with the remainder of the pulser. This sharp angle leads to a field mismatch at the interface. Sloping the switch cone would make its field distribution better match that of the Marx column and peaker arms. As was earlier pointed out, merely tilting the cone reduces the already low value of the characteristic impedance. One way around this problem would be to attach a second ground plane to the existing ground plane wedge. The cone axis can be maintained orthogonal to this tilted plane. This modification is schematically shown in Figure 6, (reproduced from [6]) which also includes a local shaping of the ground plane in the form of a "hump". The shaping is such that the electric field lines normal to the tilted ground plane are denser, resulting in a

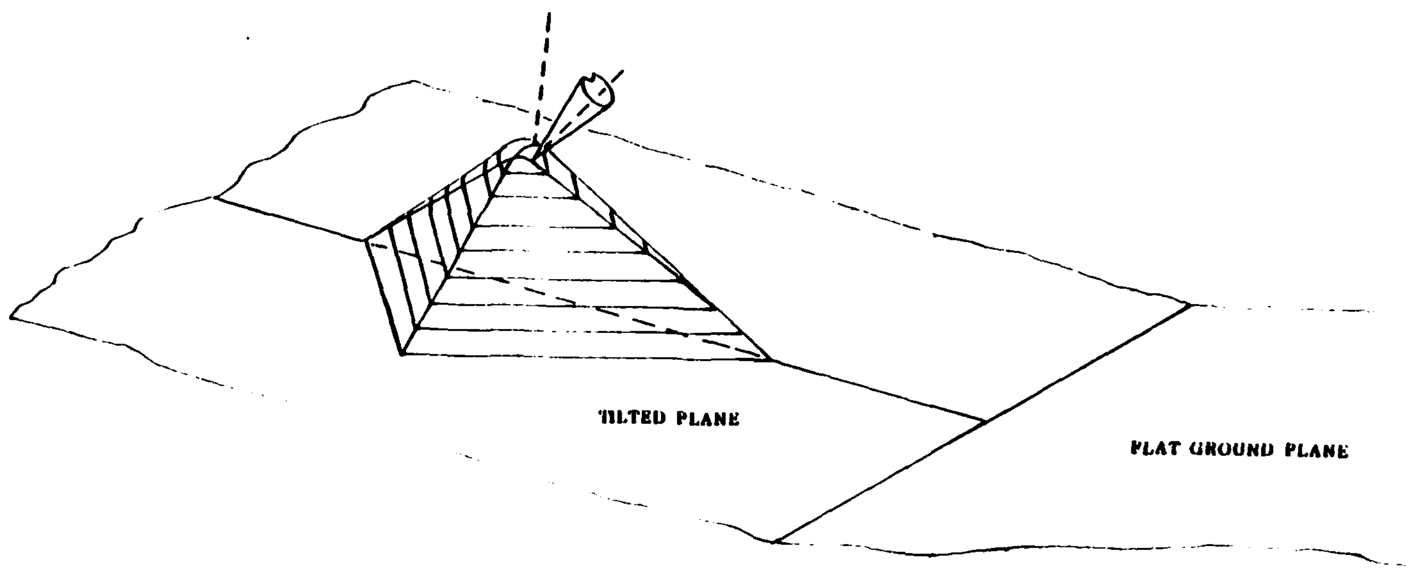


Figure 6. Local ground plane variations.

higher impedance. This method could make use of the existing switch housing, but has an artificially increased value for the characteristic impedance. One could also attempt non-circular cone cross-sections, but such attempts are best made in a controlled laboratory environment.

Examination of the data shown in Figures 5A and 5B leads one to the conclusion that the risetime of the existing switch used in the TRESTLE pulsers is no greater than 6 nS. Calculation of the anticipated risetime from a switch of this design leads to a somewhat shorter risetime. Therefore it appears that the switch itself is unlikely to be the primary cause of the undesirably slow risetime seen in the working volume of the simulator. Before any further work is done to redesign the switch area of the pulser, the experiments suggested in this report should be implemented. These should lead to definitive data on whether there is a need for switch improvements.

2. PEAKING CAPACITORS

The four peaking capacitor arms used in the Marx pulser modules serve a two-fold function of masking the inductance of the Marx generator and providing a peaking element to aid in achieving a fast risetime pulse into the simulator.

The considerations for positioning the peakers is that they all be at the same potential and that they carry equal currents. If these conditions are met, then the peaker system will offer the proper matched impedance and the inter-peaker and peaker-Marx couplings will be minimized. If these conditions are not met, several problems are likely to ensue:

* Circulating currents will flow in the peakers due to the different voltages of the peaker arms. These circulating currents will cause additional notches in the frequency spectrum.

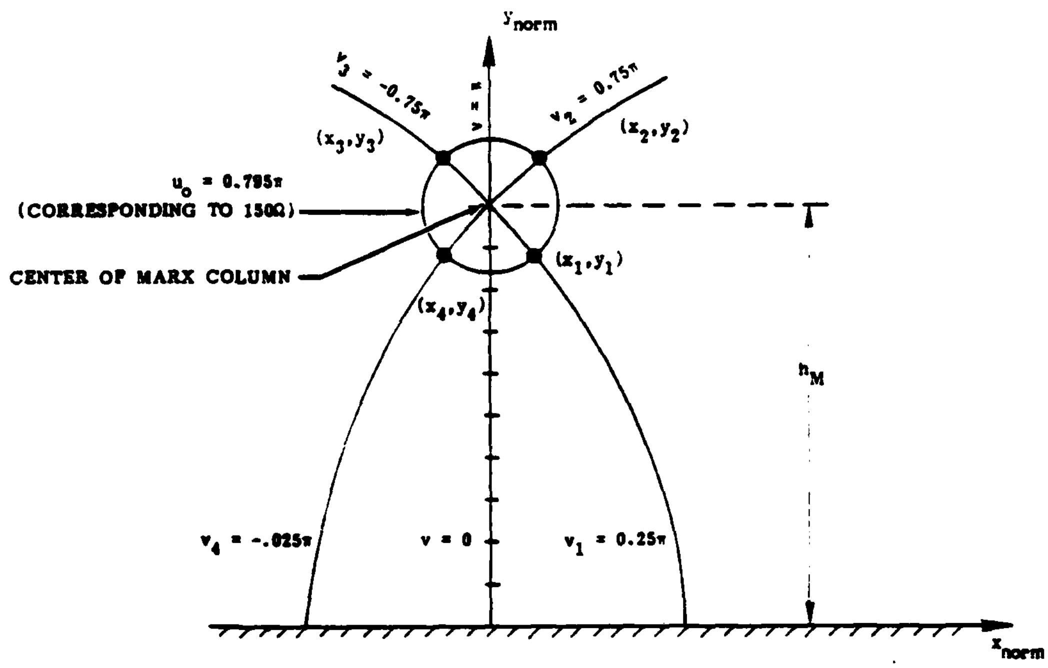
* The impedance presented to the wave will neither be uniform nor 150 Ω. This mismatch will cause undesirable reflections in the pulser array.

* Coupling between the peakers and the Marx will be increased, thereby adding to the prepulse.

The theoretical considerations have been reported in Reference [7] and also in the appendices of this report. In this section, we have carried out the computations and have shown the relative positioning of peakers for the three different cases: Number of peakers, $N_p = 4, 6,$ and 8. These cases are illustrated in Figures 7, 8, and 9, respectively. The calculation of the centers, (x_i, y_i), for $i = 1,2, \ldots N_p$ given u and v, are performed using the two equations at the top of Table 1. These equations come from the conformal transformation [8] of a line source approximating the Marx above a ground plane. Note that the Marx current is carried by this line source and the Marx column itself, approximated by a circular cylinder, forms an equipotential. In the computation of Table 1, u, the electric potential, is chosen to be 0.795π to correspond to an impedance of 150 Ω above the ground plane.

This theoretical analysis of the peaker arm locations is based upon the Marx generator as a line and is concerned with determining these locations solely on the basis of the desired impedance profile of the line. No consideration has been given to the high voltage problems attendant upon the repositioning of the peakers. The locations determined in this fashion appear to interfere with the Marx, and probably cannot be implemented as computed. The experimental program recommended later in this report should assist in determining the need for moving the peakers, adding to their number, and the best location for the arms overall.

The current location of the peakers is shown schematically in Figure A6 (page 51) along with the suggested arrangement for best electromagnetic characteristics. It seems likely that the ultimate peaker arrangement will be somewhere between the current layout and that shown in Figure 7. An arrangement similar to that is shown in Figure A4 (page 50). It should be possible to rearrange the peakers in a curve as in Figure A4 without enlarging or modifying the gas box. Moderate rearrangement of this type can very likely be done without encountering any high voltage problems if the change is extensive, the box will probably have to be enlarged to gain the needed distance from the Marx to prevent high voltage flashover.



(at the switch end)

$\underline{h_M = 1.2m}$

$(x_1,y_1) = (0.124m,\ 1.61m)$

$(x_2,y_2) = (0.157m,\ 1.338m)$

$(x_3,y_3) = (-x_2,y_2)$

$(x_4,y_4) = (-x_1,y_1)$

(at the output end)

$\underline{h_M = 2.8m}$

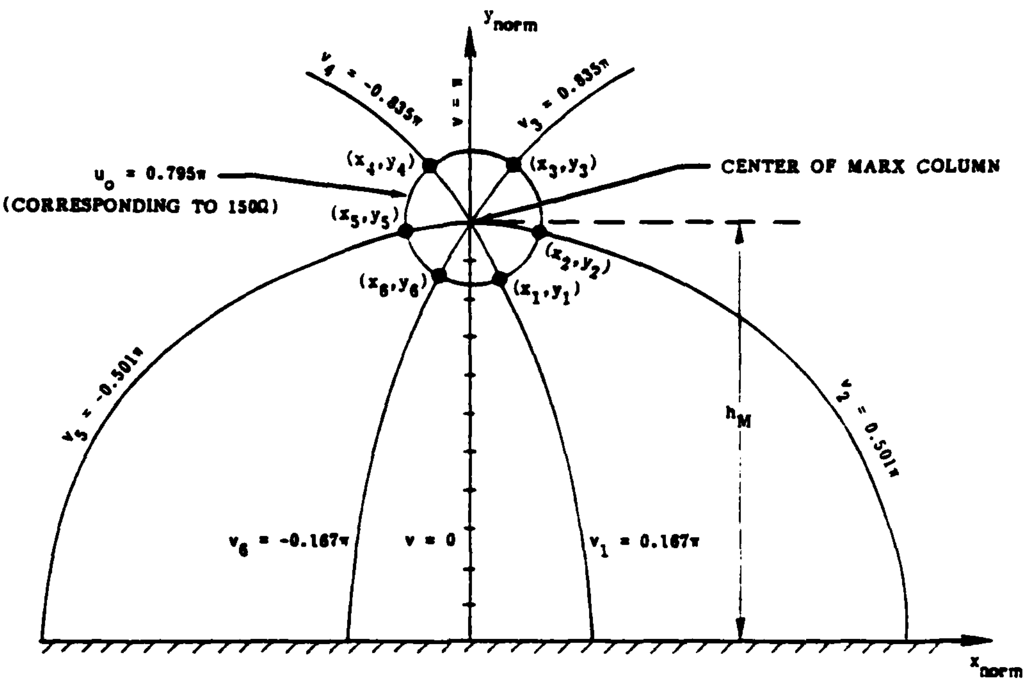
$(x_1,y_1) = (0.289m,\ 2.476m)$

$(x_2,y_2) = (0.365m,\ 3.123m)$

$(x_3,y_3) = (-x_2,y_2)$

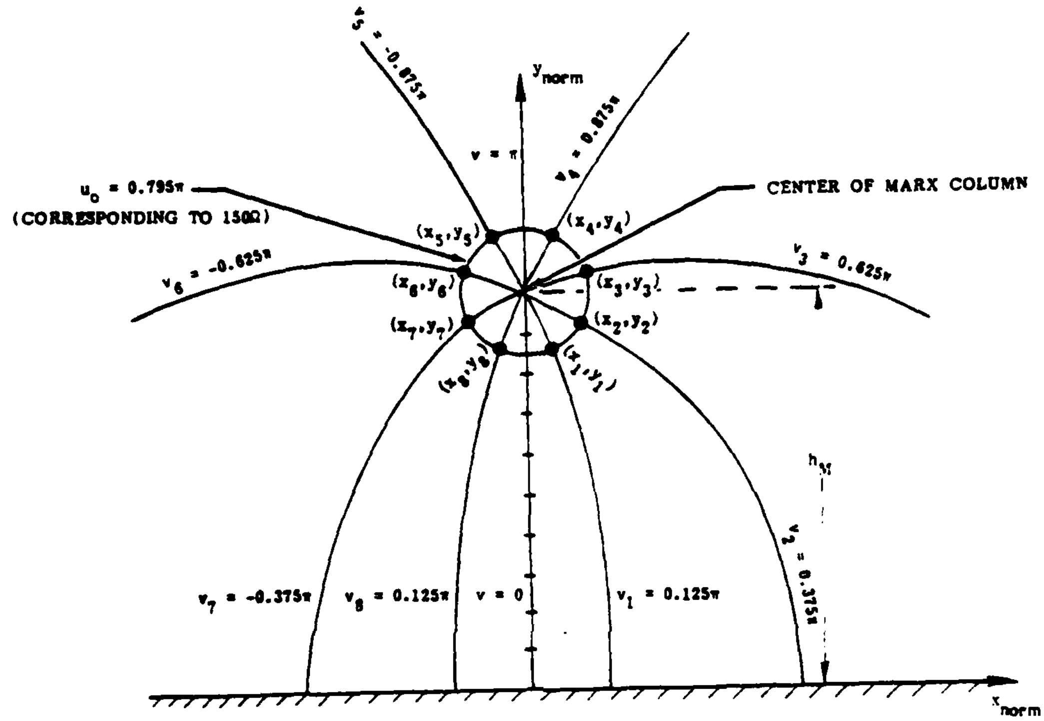
$(x_4,y_4) = (-x_1,y_1)$

Figure 7. Relative positioning of peaker arms, $N_p = 4$.



(at the switch end)	(at the output end)
$h_M = 1.2$	$h_M = 2.8$
$(x_1,y_1) = (0.086m, 1.037m)$	$(x_1,y_1) = (0.200m, 2.419m)$
$(x_2,y_2) = (0.196m, 1.183m)$	$(x_2,y_2) = (0.457m, 2.762m)$
$(x_3,y_3) = (0.113m, 1.379m)$	$(x_3,y_3) = (0.264m, 3.219m)$
$(x_4,y_4) = (-x_3,y_3)$	$(x_4,y_4) = (-x_3,y_3)$
$(x_5,y_5) = (-x_2,y_2)$	$(x_5,y_5) = (-x_2,y_2)$
$(x_6,y_6) = (-x_1,y_1)$	$(x_6,y_6) = (-x_1,y_1)$

Figure 8. Relative position of peaker arms, $N_p = 6$.



(at the switch end)	(at the output end)
$h_M = 1.2\text{m}$	$h_M = 2.8\text{m}$
$(x_1, y_1) = (0.065\text{m}, 1.028\text{m})$	$(x_1, y_1) = (0.152\text{m}, 2.399\text{m})$
$(x_2, y_2) = (0.170\text{m}, 1.114\text{m})$	$(x_2, y_2) = (0.397\text{m}, 2.599\text{m})$
$(x_3, y_3) = (0.193\text{m}, 1.262\text{m})$	$(x_3, y_3) = (0.451\text{m}, 2.946\text{m})$
$(x_4, y_4) = (0.088\text{m}, 1.394\text{m})$	$(x_4, y_4) = (0.206\text{m}, 3.253\text{m})$
$(x_5, y_5) = (-x_4, y_4)$	$(x_5, y_5) = (-x_4, y_4)$
$(x_6, y_6) = (-x_3, y_3)$	$(x_6, y_6) = (-x_3, y_3)$
$(x_7, y_7) = (-x_2, y_2)$	$(x_7, y_7) = (-x_2, y_2)$
$(x_8, y_8) = (-x_1, y_1)$	$(x_8, y_8) = (-x_1, y_1)$

Figure 9. Relative positioning of peaker arms, $N_p = 8$.

TABLE 1. COMPUTATION OF PEAKER CENTER LOCATIONS

$$x_{norm} = \left[\frac{\sin(v)}{\cosh(u) + \cos(v)}\right] \quad ; \quad y_{norm} = \left[\frac{\sinh(u)}{\cosh(u) + \cos(v)}\right]$$

N_p	u	v	x_{norm}	y_{norm}	$x = h_M x_{norm}$	$y = h_M y_{norm}$
4	0.795π	0.25π	0.1035	0.8844	0.389m	2.476m
		0.75π	0.1306	1.1154	0.365m	3.123m
		-0.75π	-0.1306	1.1154	-0.365m	3.123m
		-0.25π	-0.1035	0.8844	-0.289m	2.476m
6	0.795π	0.167π	0.0717	0.8642	0.200m	2.419m
		0.501π	0.1634	0.9865	0.457m	2.762m
		0.835π	0.0944	1.1498	0.264m	3.219m
		-0.835π	-0.0944	1.1498	-0.264m	3.219m
		-0.501π	-0.1634	0.9865	-0.457m	2.762m
		-0.167π	-0.0717	0.8642	-0.200m	2.419m
8	0.795π	0.125π	0.0543	0.8571	0.152m	2.399m
		0.375π	0.1421	0.9284	0.397m	2.599m
		0.625π	0.1611	1.0523	0.451m	2.946m
		0.875π	0.0736	1.1620	0.206m	3.253m
		-0.875π	-0.0736	1.1620	-0.206m	3.253m
		-0.625π	-0.1611	1.0523	-0.451m	2.946m
		-0.375π	-0.1421	0.9284	-0.397m	2.599m
		-0.125π	-0.0543	0.8571	-0.152m	2.399m

The peakers can be moved at minimal expense. Probably such a move would cost no more than $5,000. If more peakers of the existing type are needed and can be emplaced without modifications to the gas box, they would likely cost about $15,000 per added arm once the location was selected. Modifications to the gas box, if small in scope, are not expensive; a bulge could be added to any wall for no more than about $10,000. If any extensive changes were to be made, the gas box should probably be replaced entirely with a new box. Such a box, which might be substantially larger than the current one, would likely cost about $50,000-$100,000. All these estimated costs are for modifications to one side only, and must be doubled for the totals. The design of the fiberglass box and supports is very straightforward and presents no problems unless the box size is so greatly enlarged as to require additional structural support, in which case an additional allowance must be provided for the mechanical design and added wood and other structural materials and construction.

3. SUMMARY OF REPORTS

This theoretical study was undertaken for the purpose of determining where the known deficiencies in the TRESTLE working volume EM environment had their origins. It is generally believed that the large prepulse, slow risetime, and notch after peak seen in the TRESTLE waveform are all caused by some problems in the TRESTLE pulser system. For example, it is frequently stated that the slow risetime of the TRESTLE EM waveform could be corrected by providing a new main switch with a faster risetime. Furthermore, many of the previous suggestions for TRESTLE waveform improvement have been put forward with no consideration of the high voltage problems in the system.

The guidelines for this study, therefore, included the requirement that the system problem areas be examined by a group of high voltage experts who could keep in mind the need for feasible suggestions and who would examine the available data primarily from the pulser area. Those involved were also asked to provide suggested experiments designed and intended to yield better answers than have been available up to now. Ultimately, the intent was to develop an experimental program which would yield the data needed to redesign or rebuild the TRESTLE pulser systems in order to yield the desired waveform. Recommendations were also sought regarding the feasibility of rebuilding the system versus designing a complete new pulser system for TRESTLE.

Those involved included:

John Shannon, Maxwell Laboratories, Inc.
Ian Smith, Pulse Sciences, Inc.
Walter Crewson, Pulsar Associates, Inc.
Tom Naff, Physics International Company

In their examination of the problems with the TRESTLE waveform, Physics International (PI) states that the problems stem from two primary causes. The prepulse and risetime flaws are deemed to arise from the peaking capacitors; the notch in the waveform is judged to be due to closure of the main switch at the wrong time relative to the peak current in the Marx-peaker circuit ringup.

PI states that the length of the peakers leads to a larger than desired distributed capacitance which is charged as the peakers are charged, and which produces the large prepulse (in conjunction with the stray capacitance due to the main switch). In addition, they feel that the peakers may not be well suited for the propagation of the true main switch risetime due to such factors as their high wave impedance and inductance.

PI suggests that the output waveform can be improved by replacing the long peakers with shorter ones possessing lower inductance and wave impedance, and probably arranged differently in the system. Once that has been done, the appropriate firing time may be selected in order to reduce the depth of the notch after peak.

Maxwell Laboratories, Inc. (MLI) states that the problems with the waveform are largely due to the peaking capacitors, which they see as being probably too low in capacitance, possibly possessing resonances which lead to the waveform notch, and also possibly too long or wrongly placed. MLI also believes that some of the problem may be due to a poor impedance/transmission line match between the peakers and the output transition.

Pulsar Associates, Inc. shares the general belief that the prepulse is largely due to the too-rapid charging of the peakers, but also expresses the opinion that some of the prepulse is due to "fizzle" in the main switch as its voltage rises. They point out that adding both capacitance to the peakers and inductance to the overall Marx-peaker circuit is necessary to most effectively reduce the magnitude of the prepulse. They feel that adding ultraviolet illumination to the main switch at the appropriate time will reduce the fizzle, and that the overall jitter of the switch need not increase significantly if the illumination is properly timed.

Pulsar is also of the opinion that no further experiments or measurements need be made in the existing system in order to make substantial improvements in the output waveform.

Pulse Sciences, Inc. is also convinced that the peakers are too low in capacitance, and that they are not properly placed to share current equally. They are concerned about the unequal current sharing, and suggest the addition of cross-connections, perhaps with a resistive material, in order to damp out some or all of these circulating currents.

Pulse Sciences is concerned about the probable reflections due to the sudden impedance mismatch at the junction between the peakers and the output transition section, and they suggest the addition of peaker elements in such fashion as to smooth this connection.

Pulse Sciences believes that the output switch could well be improved, probably to the form of a tilted monocone over the ground plane. They share the general opinion that more peakers are needed with improved placement in order to share current more nearly equally.

Finally, they mention the effects of the wood of the deck in stripping high frequencies from the incoming pulse.

In LuTech's consideration of the problems in the TRESTLE waveform, it is pointed out that the dip after peak can likely be reduced by improving the transition between the peakers and the output transition section. They believe that both improving the impedance of the main switch (toward 150 Ω) and also improving the transition from the main switch to the Marx and peakers will improve the high-frequency performance of the simulator. LuTech is strongly in favor of moving the peakers in order to place them on an equipotential surface.

IV. EXPERIMENTAL PLAN

The experimental plan described in this section is a minor modification of that proposed by Pulse Sciences, Inc. It has been altered slightly in order to more efficiently utilize the time available from January 1981 to the next scheduled use of the TRESTLE simulator for aircraft testing, in Spring of 1982. This opportunity to measure, test, modify as needed, and retest in the TRESTLE facility may not appear again, and it is felt that this time is extremely valuable for determining what to do to improve the facility performance.

The test plan, which appears in Figure 10, is initially concerned with measurements of the TRESTLE waveform in the current configuration, both at the 75 kV or higher charge level, and also at some lower level at which the pulser operates properly but at which measurements and modifications can be made which might prove to be damaging to the system at higher voltage. It is hoped that at this lower level SF_6 will not be needed in the pulser gas boxes. Operating without SF_6 would permit much more efficient and rapid testing and modification to be performed, thereby expediting the series of desired tests greatly.

As can be seen from the plan, the first task involves the extensive and detailed determination of a baseline at both the high level of charge and the minimum mentioned above. There are some data which suggest that the actual risetime of the existing main switch is less than 5 ns. If this possibility is confirmed during the baseline measurements, it may not be necessary to look further into main switch improvements or modifications. In such a case, efforts can be directed toward determining what happens to this relatively rapid risetime to prevent its appearance in the working volume of the simulator. These measurements will also yield data for later use in the evaluation of the proper switch firing angle.

The measurements needed here are intended to document the changes, if any, of the radiated and bounded waves as they travel down the pulser wedge. In order to perform these measurements, several sensor placements are called for which have not been provided to date. The measurements to be made on the ground plane should be very simple to perform, since the area in which the sensor will be placed

TEST 1: BASELINE MEASUREMENTS

Data taking with several sensors; several locations, analysis of data; decision regarding pulse injection.

TEST 2: PEAKING CAPACITOR RELOCATION

Data taken with peakers added or relocated, main switch fired early, on-time, late.

TEST 3: PULSE INJECTION TESTING

Uses fast pulser to determine possible risetime improvement.

TEST 4: SWITCH INVESTIGATION - ADDED PEAKERS

Determine optimum switching time with optimum peaker number and rearrangement.

TEST PLAN

NO

YES

Figure 12. Test plan for TRESTLE.

can easily be reached from the pulser level behind the ground plane. The location in the ground plane for the sensor may be reinforced with wire screening or even metal sheet and the sensor put in place just projecting above the ground plane the required amount. A very short cable may then be used to connect the sensor to an oscilloscope inside a screen box, and the needed measurements made easily. The measurements need not be made all at once, since that would require altogether too many people and too much equipment, but it is important that at least the sensors nearest the pulser be used at the same time as the sensor in use further down the line. In this way, for every shot studied, there will be records of the pulse waveshape both at the pulser as launched and further down the array, as modified by its travel to that point.

The following is a list of locations suggested for the initial measurements. If some of these prove to be impractical or show no alteration of the waveform from the previous measurement, it will simplify the data taking.

1. HSD-3 sensor currently in place 1.07 m from the main switch centerline.

2. HSD-3/MGL-5 sensor located on the ground plane midway along the peaking capacitors and on their centerline.

3. Same as (2), but close to the junction of the peakers and the output transition.

4. Same as (2), but located just past the output transition.

5. Current sensor location LSE/LSW, 23.77 m from the pulser apex.

6. Current sensor location, NE/NW, 97.23 m from the pulser apex.

All the above measurements should be made at both 75 kV and the lowest usable charge levels, in order to develop a proper baseline for the later tests. In addition, these measurements should be made for shots fired at early, optimum, and late switch times, in order to help determine the optimum times for firing once the circuit parameters have been changed in the later tests.

If the tests planned for this baseline determination lead to the conclusion that Test 3 should be performed, then at that time planning can be undertaken to specify and procure the appropriate pulser. This change in timing for the pulser injection tests from the plan by Pulse Sciences is due to the time anticipated to be required for the procurement of the needed pulser, since it may have to be designed or modified for the projected usage in the TRESTLE investigation.

Once the baseline tests of Test 1 have been completed, and the decision/evaluation of the requirements for Test 3 are underway, Test 2 may be performed. This test, which is essentially the same as the Task 3 in Pulse Sciences' plan, involves the addition/relocation of peakers within the gas box of one of the pulsers.

The purpose of this test is to determine whether additional peaker arms will improve the wave propagation within the gas box and also whether the prepulse and notch will be affected in the expected way by the added capacitance.

Let us examine these effects separately. It appears that the existing peakers may not be properly arranged with regard to the transmission line impedance they present to the wave. In addition, it appears likely that they are not adequate in number or location to drive the output transition properly without major reflections. Therefore, the addition of more peaker arms, either in the current planar array or more likely in an arrangement similar to the equipotential surface array already discussed in this report, will improve the propagation of the wave down the pulser. The other effect, that of the actual capacitance added by more peaker arms on the circuit behavior, is easily determined by these tests. The added capacitance will slow the rate of charge of the peakers by the Marx, and therefore should reduce the magnitude of the prepulse. In addition, the increase in the capacitance charged up by the Marx will increase the energy stored in the peakers available for "prompt energy" driving the early part of the output waveform. Thus the early part of the wave may last longer and help fill in the notch after peak.

If necessary or desirable, the peakers may also be added outside the gas box. It is well to point out at this time that the structure of the gas boxes is such that penetration through the wall of the box for these purposes is neither difficult nor expensive, and the holes or slots needed for those tests can easily be patched and sealed later. If it is useful to locate any portion of the high-voltage circuit outside the gas box, it will of course be necessary to operate it at a level which will not flash over in the ambient atmosphere of the TRESTLE, which is at approximately 5000' above sea level.

Test 3, which is the injection of a fast-rising pulse into the TRESTLE array at various points from the apex of the pulser forward toward the peakers, in the fashion detailed in the Pulse Sciences' report, will then be undertaken if the results of Test 1 indicate merit in so doing. The baseline field and waveform measurements made in Test 1 will make these tests simpler, since the appropriate sensor placements and the needed measurements will have been determined during that portion of the testing.

The purpose of this test is to determine, using a fast-rising clean pulse, the areas within the existing pulser system which cause reflections and the best new arrangements for components such as added peaker arms. These tests would start with a baseline set of measurements to establish the response characteristics of the present system; in effect a high voltage Time Domain Reflectometry measurement would be made, but with the sensors at various locations along the ground plane as described in Test I.

Once these measurements have been made, the same pulse could be injected into the modified system and fine tuning performed with regard to location of added arms, added sheet metal, transition reshaping, or even main switch rearrangement. The differences in the pulse propagated will yield data on the best arrangements for further testing or implementation at megavolt levels without the need for SF_6 in the gas box and also with no risk of damage to the pulser. In addition, these low-level tests can be performed with far fewer personnel and much simpler procedures than tests performed with the Marxes operating.

Another measurement which can be made at this time is the injection of the external pulse with the peakers covered with foil or replaced with metal tubes of the same approximate size and shape. Such a test would show what portion of the pulse propagation is due to the peaker location and shape and what part is due to the peaker internal construction and resonances.

Test 4, the switch investigation with the optimum number and placement of peakers, may then be performed in order to determine the appropriate switching time for minimum notch/prepulse. These tests should be performed at reduced voltage until the appropriate time has been determined, then at the full voltage of the pulser if possible.

The purpose of this test is to determine the performance available for the most nearly optimum configuration possible based upon the data thus far taken and the components available at this time. Probably this test will be performed with several peakers added and also with the existing peakers rearranged as determined earlier. Once the arrangement has been decided on and accomplished, the pulser will be operated at low voltage and measurements made using the same sensors as in the preceding tests. If desired, measurements may also be made in the working volume in order to determine that the results have meaning in terms of the test volume.

The switch firing time will be varied over a range sufficient to determine the feasibility of eliminating the notch by choosing the proper firing angle. At the same time, the prepulse may be observed to determine whether the improvement is adequate. Risetime will also be measured at this time, since the improved arrangement should lead to propagation of a faster risetime if the switch is not the limiting factor.

Finally, tests can be performed with the pulser system operating at or near full voltage, in order to verify the usability of the modified system. The feasibility of the higher voltage testing must be carefully evaluated prior to full charge in order to avoid the possibility of damage to the system or its components.

The test program outlined herein is rather extensive, and cannot be performed at all without the complete availability of the TRESTLE simulator facility for a period of at least 6 months. During this time the tests and temporary modifications will be performed. At the end of the tests, the pulser systems will be restored to their original configuration and readiness for testing. It is estimated that the entire sequence of tests can be performed for approximately $250,000 and 6-8 months. This time includes all testing, procurement of needed items, report writing, and restoration of the pulsers to their original status. The estimated cost does not include the cost of instrumentation and other similar equipment which is expected to be GFE to the contractor.

Once all these tests have been performed, the entire program and its results should be evaluated and final determination made of the modifications to be implemented at the TRESTLE. If the improvement in the waveform is adequate with the changes suggested and evaluated in these tests, then the modifications should be made as soon as possible in order to make the TRESTLE useful at once. If the improvements are not sufficient, then the data gained from the test series may be studied to determine whether the desired level of improvement can be gained using the existing pulsers. It may be that the improvement wanted is unobtainable without major redesign of the pulsers or the array, although this is unlikely.

V. PULSE POWER TECHNOLOGY CONSIDERATIONS

1. PEAKER RELOCATION/ADDITION

This modification, either temporary or permanent, has been suggested as a helpful method for the improvement of the output waveform. It is therefore very important to determine how easy or feasible it is to do.

During normal operation of the TRESTLE pulsers in the past at the 75 kV charge level, frequent flashovers to the peaking capacitors from the Marx were encountered. These flashovers usually, but not always, occurred between the Marx and the peaker in the area where a peaker support column was placed between the pulser and the peaker arm. These flashovers often damaged the support columns, and invariably destroyed at least one peaking capacitor. Once this problem area was defined, the peaker support columns were relocated to place them on the ground side of the peaking arms, thereby removing the columns from the path of such flashover and also avoiding their contribution to the likelihood of flashover. Since this relocation, the frequency of these flashovers between the Marx and the peakers has dropped considerably. Nonetheless, the area is still very highly stressed especially if there is any variation in the sharing of current among the peakers and the resulting nonuniform distribution of voltage along the peaking arms.

For these reasons, moving peakers around, even in about the same plane as their present location, is not as simple as it might seem to be. The initial experiments along these lines should be done at reduced voltage, and the results watched very carefully. Indeed, if it is at all possible, the entire set of experiments should be done at reduced voltage, and higher voltages tried only when a peaker arrangement has been found which deserves the risk of full-charge operation. Similarly, for the experiments wherein the output switch is fired late, the higher charge levels should be avoided due to the danger of major damage. Furthermore, if it is at all possible, these peaker rearrangement tests should be made with air in the gas box. The operational simplicity and relatively low cost of experiments performed under those conditions are worth striving for, especially in a series of experiments as long and complicated as those under discussion here.

Another factor to consider in the moving of the peakers is how to mount them in the pulser system. If it is desired to simply add them in parallel with the existing peakers, the added elements may be simply tie-wrapped to the present arms. If different locations are needed, the added peakers may be suspended by means of dielectric lines or with such materials as Extren or Lucite. This conceptually simple method of arranging and supporting the added peakers must be carefully done, however, since even these materials will flash over if the field stresses and arrangements of the arms are not right.

In the event that it is decided to short out some of the individual peaking arms with foil, the ends of the foil wrap must be carefully controlled in order to avoid field enhancement at these locations. If this care is not taken, the entire arm is likely to flash over, even at lower charge voltages. Such events could prove to be very expensive and time-consuming, and should be avoided.

2. PEAKER CROSS-CONNECTION

Implementation of this scheme should present little difficulty; the voltages between the peakers should not be too large, and the connections between them should tend to reduce these differences, even if the interconnections are resistive. The only matter to be concerned about is the preservation of a good field distribution facing the pulser; in order to do this, the connections need to be smooth and rounded, and not protrude in the direction of the Marx. No difficulties are anticipated in accomplishing this.

3. PEAKER CURRENT MEASUREMENTS

The suggestion has been made that the individual peaker currents might be of interest in the effort to improve the overall pulser performance. These currents have never been measured in the TRESTLE pulsers, although peaker current has been measured in the HAG-IIC pulser with considerable success.

The probable method to be used here is to construct some type of current viewing resistor (CVR) to install at either end of the peaking capacitor. The voltage developed across the calibrated resistance of the CVR may then be transmitted to an oscilloscope, most probably by means of a Fiber Optic (FO) link, battery operated and suitably hardened against the EMP environment anticipated. Such FO links exist, and can probably handle the necessary bandwidth and dynamic range. The peaker current can be expected to have a maximum rise or fall of perhaps 5 ns, and a current peak in one arm of about 6000 A at 75 kV charge and 90 ns switch firing time. The CVR would then be designed to have a resistance of about 10 mΩ, yielding a signal of 60 V, which would be reduced again by the matching network. The design of the CVR might very well be the frequently used method of arranging a large number of small carbon resistors in parallel around a cylindrical insulator, thereby arranging for symmetrical current sharing and ease of calibration.

The only real problem seen in this measurement is the placement of the FO transmitter so that it is neither exposed to excessive EM fields, nor the cause of flashover which would probably be damaging to both the transmitter and the pulser components. FO transmitters are available which are small enough to permit safe placement at either end of the peaker arms, although probably none is available which is small enough to be placed near the middle of a peaker.

4. MARX CURRENT MEASUREMENTS

The factors which apply to the measurement of the individual peaker currents apply here, with the only change being the magnitude of the current, which is about 24,000 A. A similar CVR could be constructed for the connection at either end of the Marx, and it is also possible to place such a CVR between the two Marx modules, since there is a space between them which should be a reasonably field-free region, at least compared to other places not far away.

5. OUTPUT SWITCH CURRENT

This measurement will be similar in nature to the Marx current measurement. The differences here lie in the size of the CVR to be used, and the fact that it may also be necessary to make it in some way part of the pressure vessel. If that is the case, there will be increased difficulties with the mechanical design, since the pressure vessel must reliably contain the 690,000 Pa (gauge) pressure of the main switch environment. No major difficulties are seen here, however, if the measurement is to be made.

6. STEP-FUNCTION PULSER

If it is necessary to perform the experiments described in Test 3, the injection of a fast-rising pulse into the TRESTLE array, the maximum voltage pulse obtainable with the desired risetime must be considered. If the assumption is made that a pulse is needed with a risetime of 3 ns (10-90%), then the maximum voltage readily obtainable is probably about 100 kV. Even so, we know of no pulser commercially available off-the-shelf which will deliver these characteristics into the 150-Ω array of the TRESTLE. The pulser will therefore need to be designed and built once it is determined that it will be needed. This is the reason for providing the time for the peaker rearrangement testing while such a pulser might be procured. It is probable that a pulser with the desired output characteristics could be designed and built in about two months if the requirements for triggering and repetition rates were lenient enough. Since the injected pulse probably need not be synchronized with anything to greater accuracy than a few seconds, the output switch of the pulser could be designed to fire by reduction of its pressure, a simple and inexpensive technique. In this fashion, the needed pulser could be obtained without major expenditure of funds or time.

It might also be possible to perform the needed measurements with still lower fields in the TRESTLE than would be yielded by a 100 kV pulser, and this alternative should be explored. A 50 kV pulser could undoubtedly be obtained considerably more quickly and inexpensively than one with twice the voltage, and the 50 kV pulser could have a substantially faster risetime as well.

7. MAIN SWITCH JITTER

If it is necessary to increase the inductance of the Marx-peaker circuit, and to increase the capacitance of the peakers, the ringing frequency of the circuit will be reduced. If this frequency is very much reduced, the main switch will have to be fired later even to preserve the current firing angle; and it may be desirable to increase the firing angle as well. In this event, the main switch will see a much slower and longer application of voltage across it. This change may lead to two problems; increase in the likelihood of flashover outside the main switch, and increase in jitter in the closure of the main switch.

For these reasons, the suggested test plan includes testing the main switch for jitter problems at lower than normal charge levels. The increase in the time to main switch closure will place the ultimate firing of the switch at a time when the voltage is rising more slowly than at the current firing angle. Firing the switch at that time should yield a good indication of the jitter increase that may be expected if the switch is fired with this rate of rise of voltage, which could be arranged to correspond closely to the anticipated rate of rise for a higher charge level and later time of firing. These tests should enable some determination to be made of the likely increase in switch jitter we would expect to see if the switch were regularly to be fired later than presently.

Additionally, a study can be made at that time to determine the likely flashover voltage of the main switch with the waveform anticipated with the new circuit constants. However, as long as the pulser charge level is kept at the present levels, there is probably little to fear from external switch flashover. The switch was designed to be operable at 5 MV, and the firing angle would have to be considerably delayed in order to present the switch with a stress to equal that.

VI. CONCLUSIONS AND RECOMMENDATIONS

The work performed under this subtask has demonstrated the general agreement among those consulted regarding the solution for the problems of the TRESTLE simulator. All agree that the probable primary area for improvement of the TRESTLE waveform lies in the peaking capacitor circuit parameters and geometry. Other problems, such as the geometry of the pulser and the main switch impedance, are seen to be of lesser importance. There is also a strong belief that the output waveform can be substantially improved with today's technology, probably without the need to make major modifications such as new pulsers or gas boxes.

An experimental program has been presented which should yield the needed information with the minimum time and maximum efficiency and cost effectiveness. It is recommended that the work begin as soon as possible, since the current idleness of the TRESTLE presents the ideal opportunity for the tests and measurements needed. The TRESTLE may not be available for this necessary time again; indeed, if the tests and measurements lead to the expected improvements, the TRESTLE will undoubtedly be in much greater demand in the future.

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APPENDIX A

TRESTLE PULSER IMPEDANCE PROFILE AND PEAKER ARM LOCATION

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I. IMPEDANCE PROFILE

The objective here is to estimate the impedance profile as one moves from the base of the output switch to the terminator at the far end of the ATLAS I (TRESTLE) facility. The longitudinal dimension of the facility is 410 m from pulser apex to the apex of the output conic section. A line schematic diagram (from Reference [1]) of this simulator facility is shown in Figure A1. All the dimensions indicated in this figure are in meters, and the rectangular coordinate system originating at the center of the working volume is also indicated. The principal components of the electric and magnetic fields are E_x and H_y, and the dominant TEM wave propagates along the positive z axis. The principal dimensions of the simulator facility are summarized below:

$$\begin{aligned}
&\text{Horizontal length of the input conic} \equiv L_i \cong 90 \text{ m} \\
&\text{Half separation of the central plates} \equiv b = 52.5 \text{ m} \\
&\text{Half width of the central plate} \equiv a = 17 \text{ m} \\
&\text{Horizontal length of the output conic} \equiv L_o \cong 172 \text{ m}
\end{aligned} \tag{1}$$

resulting in

$$(L_i/b) = 1.71;\ (b/a) = 3.09;\ (L_o/b) = 3.28 \tag{2}$$

These ratios are useful in estimating the various impedances. From Figure A1, it is also observed that $x = 0$ is a symmetry plane so that the impedance from the simulator "plate" to the image plane ($x = 0$) is one half of the impedance from "plate" to "plate". The word "plate" can signify (a) the input conic AB in Figure A1, (b) the central plate BC in Figure A1, or (c) the output conic CD in Figure A1. In other words, the impedance between the central plates BC and B'C' is twice the impedance from the plate BC to the image plane at $x = 0$.

For convenience of estimating the impedance, the simulator geometry can be divided into five major sections. They are:

1) pulser
2) input conic section

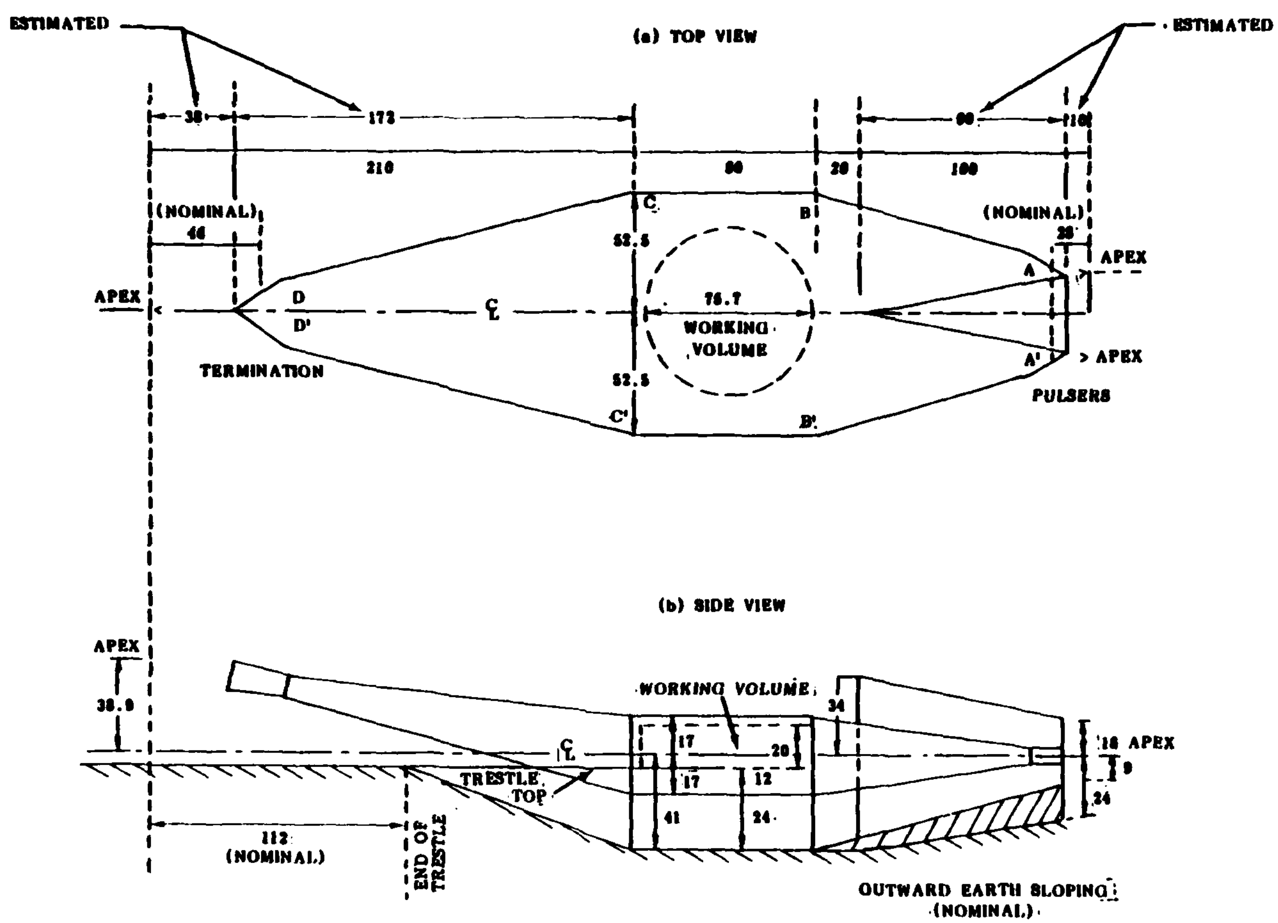

Figure A1. Line schematic diagram of Atlas 1 (TRESTLE) indicating the dimensions in meters.

3) central parallel plate section
4) output conic section
5) terminator

Out of these five major sections, only the pulser section (1) above needs further subdivision for plotting the impedance profile. We shall briefly discuss each section and estimate the principal impedances.

1. PULSER

The Marx pulser module configuration is shown in Figure A2 and it is further subdivided into: (a) monocone output switch, (b) Marx/peaker system and (c) the output transition. The principal impedance of each of these subdivisions is considered below.

a. Monocone output switch--The monocone switch design is shown in Figure A3, and it consists of a single cone over a ground plane forming a monocone antenna. The details of switch construction are described in Reference [2]. The half cone angle is 20°, which, when used in the following expression from Reference [3],

$$Z_c \cong \frac{Z_o}{2\pi} \ln \left[\cot (\beta/2)\right] \tag{3}$$

gives a characteristic impedance of 104 Ω. In the above equation,

$Z_o \equiv$ free space characteristic impedance $\cong 120\pi\ \Omega$
$\beta \equiv$ half cone angle of the monocone

Note that the 104 Ω impedance is for an untilted cone (i.e., cone axis is normal to the ground plane wedge) and the impedance is lowered if there is any tilt.

b. Marx/peaker system--In the present configuration, there are four identical peaker arms beneath the central Marx column and all five conductors are enclosed in a gas box. Strictly speaking, the characteristic impedance of such a

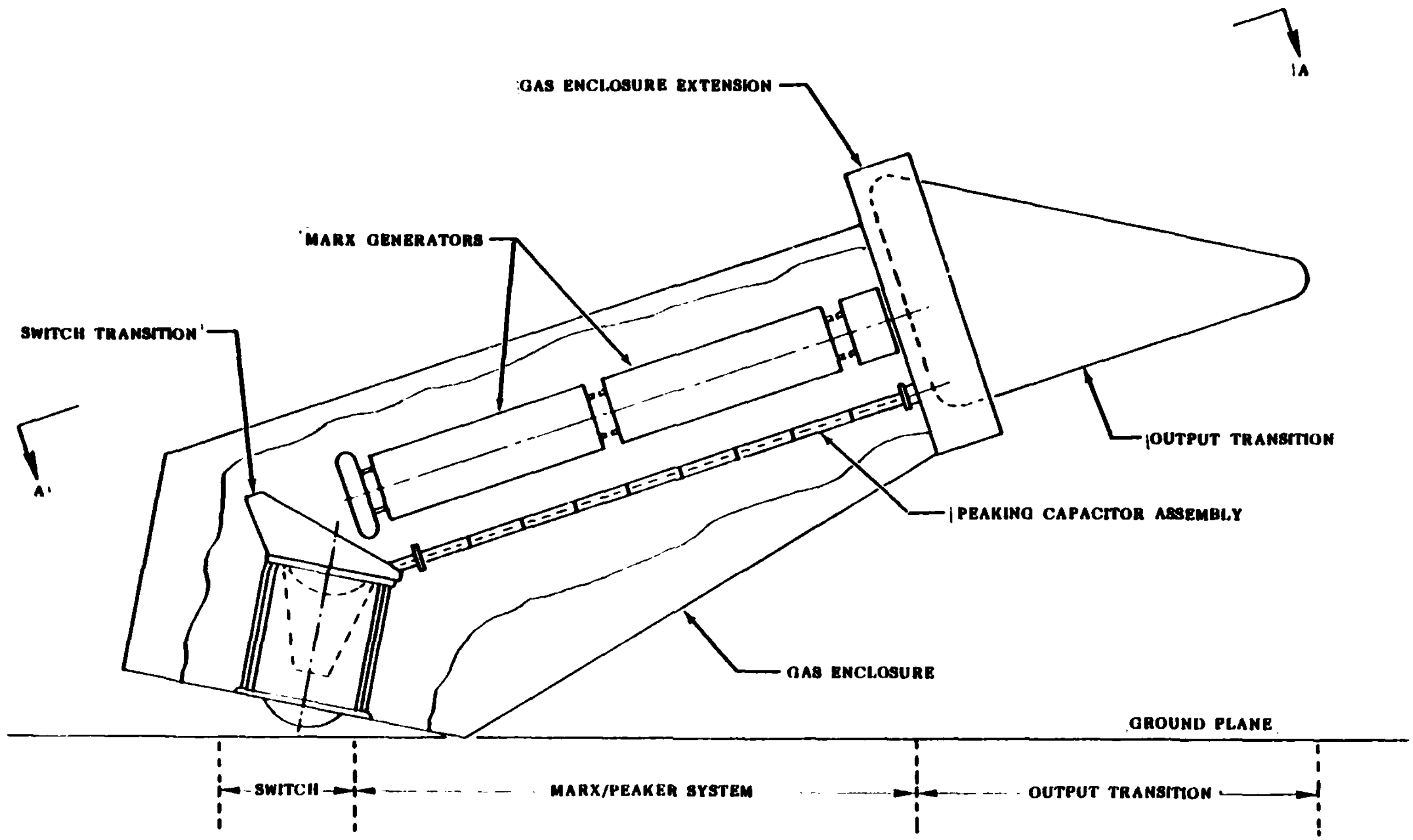

Figure A2. Marx pulser module configuration.

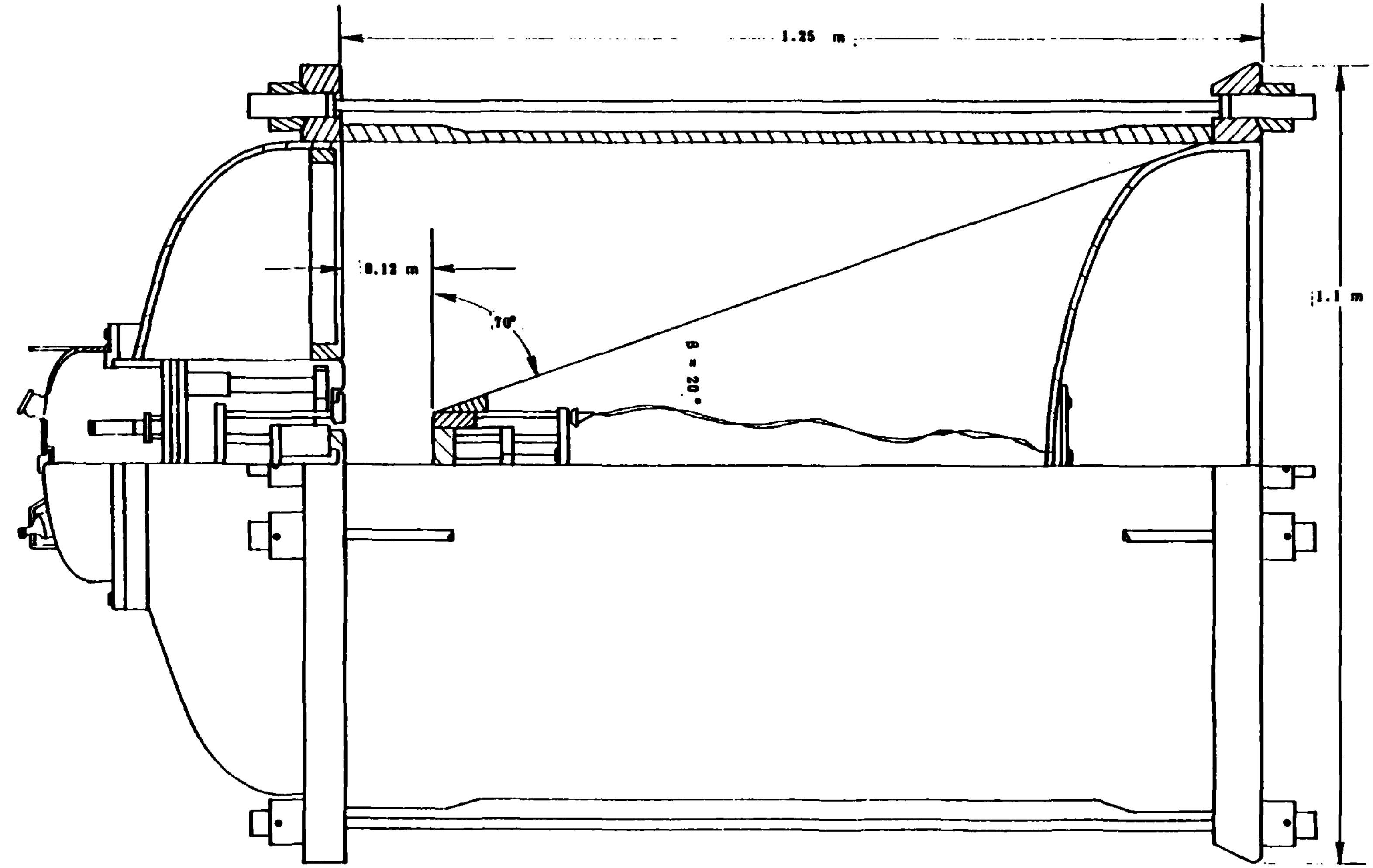

Figure A3. Schematic of the monocone output switch for the 5 MV Marx pulser.

five-conductor system is given by a 5 x 5 matrix. In terms of the distances indicated in Figure A4, the matrix elements are given by

$$Z_{i,i} = \frac{Z_o}{2\pi} \ln \left(\frac{2y_i}{a_i}\right); \quad i = 1, 2, 3, 4, 5 \tag{5}$$

$$Z_{i,j} = \frac{Z_o}{2\pi} \ln \left(\frac{d^*_{ij}}{d_{ij}}\right); \quad i,j = 1, 2, 3, 4, 5 \text{ and } i \neq j \tag{6}$$

Given the geometry, the above matrix elements are easily computed. However, for the present purpose, we seek a single value of the principal characteristic impedance for the Marx and peaker system. Before estimating this single impedance value, let us briefly look at the Marx column impedance by itself, i.e., in the absence of any coupling with peaker arms. A simple cylindrical conductor model for the Marx is shown in Figure A5. In this figure, the Marx column is shown as a cylindrical conductor of approximately 25 cm in radius and 4 m in length, slanting above the image plane, making an angle of approximately 23.5° with the horizontal. Such a conductor has a position dependent impedance given by

$$Z(z) \cong \frac{Z_o}{2\pi} \ln \left(\frac{b(z)}{a}\right) \tag{7}$$

where b(z) is the position dependent height of the conductor above the image plane. With the numbers indicated above, use of the equation (7) gives impedances of 135 Ω and 186 Ω at the ends of the Marx column with a 166 Ω impedance at the middle. However, it is emphasized that the dimensional numbers used in this estimation are crude and hence, the impedances estimated, at best, indicate the range of variation.

Next, an estimate of single impedance for the Marx/peaker system is obtained as follows. The present configuration of the four peakers beneath the Marx column, in terms of their relative orientation is sketched in Figure A6a. It is observed that presently the four peakers are located beneath the Marx, not quite on an equipotential surface. Also, the peaker arms, in all likelihood, do not carry equal currents. Consequently, the Marx is not shielded well from the ground and there is also net flux linkage between individual peakers. One way of shielding the Marx from the ground is by using the concept of a coaxial cage [4] transmission

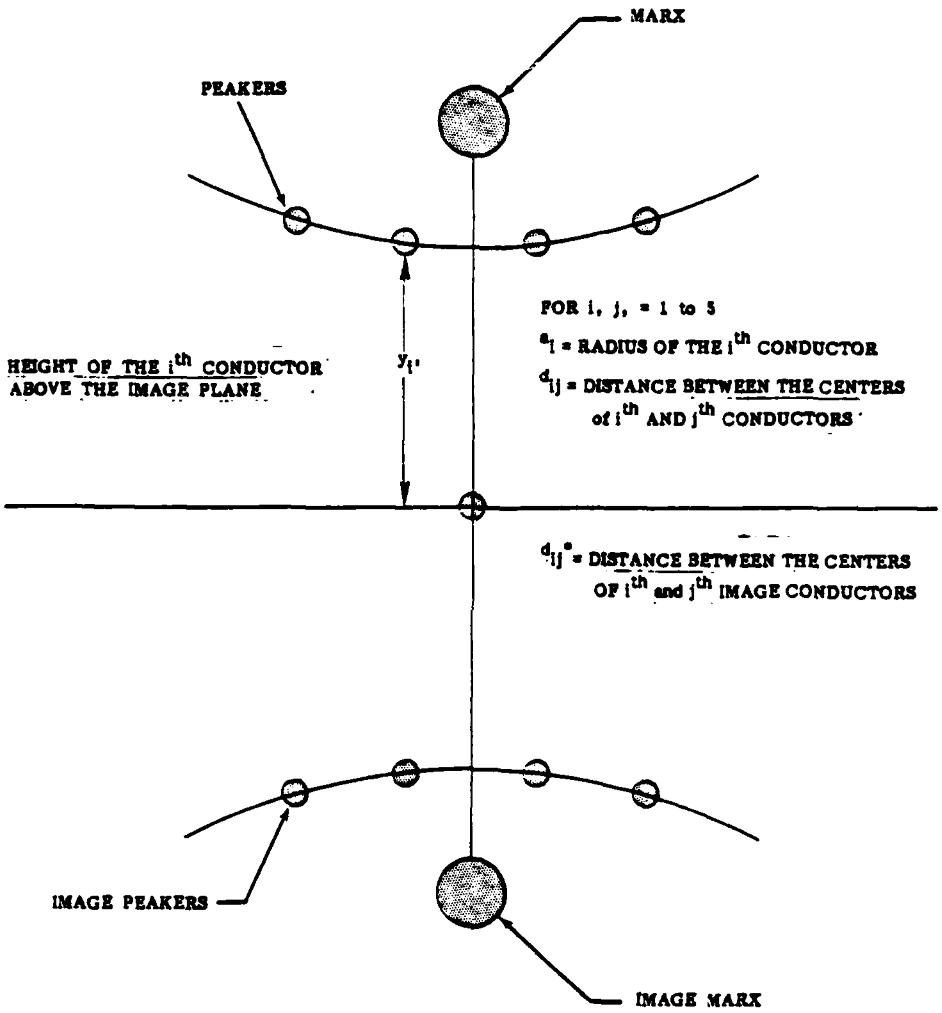

Figure A4. Existing Marx/Peaker configuration.

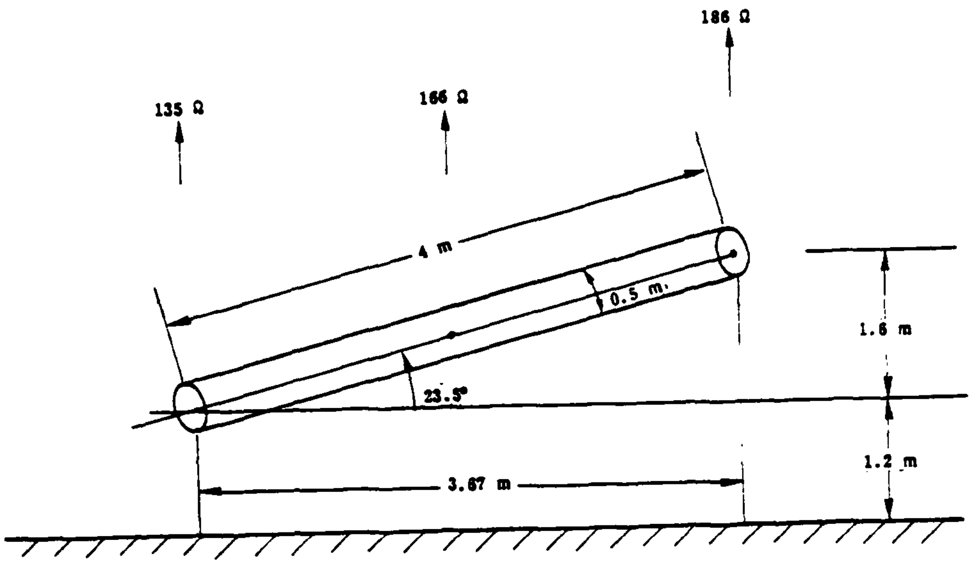

Figure A5. Approximate Dimensions of a cylindrical conductor model for Marx above a ground plane.

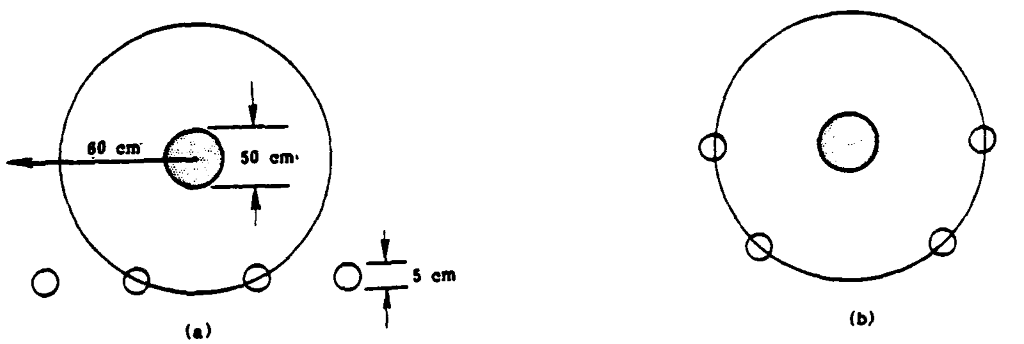

Figure A6.

(a) Approximate relative orientation of existing Marx/Peaker configuration.

(b) Coaxial cage model for estimating a single impedance for the Marx/Peaker system.

line, illustrated in Figure A6b. The inner conductor of radius a is the Marx column and 2N (or 2N + 1) identical conductors (peakers) of radius a_1 are located on a circle of radius b and operated in parallel. Such a transmission line can approximate a coaxial cable of inner conductor radius a and outer conductor radius b, if a_1 is chosen to be equal to b/2N. The subject of relative orientation of peaker arms and the Marx column will be addressed separately.

c. Output transition--The approximate dimensions of the output transition is shown in Figure A7 along with an equivalent cylindrical conductor model. With this approximate model, the impedance is estimated to vary from $\sim$ 120 Ω to about 139 Ω on the simulator side.

2. INPUT CONIC SECTION

The input conic section is a transmission line whose TEM mode of propagation has been analyzed by Yang and Lee [5] and Yang and Marin [6]. These two references deal respectively with the impedance and field distribution of the conical transmission line. The characteristic impedance plot from reference [5] is reproduced in Figure A8 for present use. It is seen from this figure that the two ratios (L/b) and (b/a) uniquely determine the impedance. These ratios were previously computed for the input conic section as $(L_i/b) \cong 1.71$ and $(b/a) \cong 3.09$. From Figure A8, for these values, one has a plate to plate impedance of about 302 Ω or, equivalently, the characteristic impedance of the input conical plate with respect to the image plane $x = 0$ is $\sim$ 151 Ω.

3. CENTRAL PARALLEL PLATE SECTION

The TEM properties of finitely wide two-parallel plate transmission line was extensively analyzed and the results of an extensive parametric study were reported in Reference [7]. From Table 4.1 of this Reference [7], the characteristic impedance of the central parallel section is about 150 Ω for the half section.

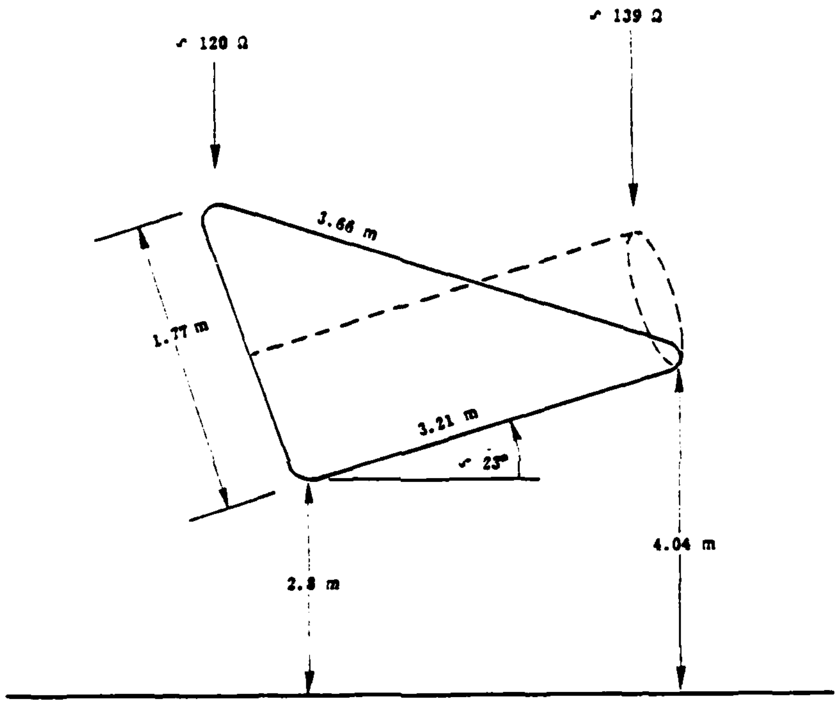

Figure A7. Approximate dimensions of the output transition and an equivalent conductor model.

4. OUTPUT CONIC SECTION

This section is similar to the input conic section in terms of the TEM characteristics. The values of (L_o/b) and (B/a) are now given by 3.28 and 3.09 respectively. Once again, using the impedance plot of Figure A8, the half section impedance of the output conic section is also about 151 Ω.

5. TERMINATOR

The terminator construction is symmetric with respect to the ground reference in the middle. Each side has seven parallel resistances R and each R is composed of fifteen 70 Ω resistors in series. This series parallel combination of resistors result in an impedance of 150 Ω per side or 300 Ω from plate to plate. Also, this impedance of 150 Ω for the half section, matches the propagating TEM wave at low frequencies, and the intrinsic inductance of the terminator is estimated to be 2.73 μH [8].

Collecting the results of all the impedance estimates, the impedance profile is shown plotted in Figure A9. It is seen that all of the individual sections of the simulator, namely the input/output conic section, central parallel plate region and the terminator, have nearly 150 Ω principal or characteristic impedance. The deviations from the nominal 150 Ω for the half section impedance occur in the pulser components.

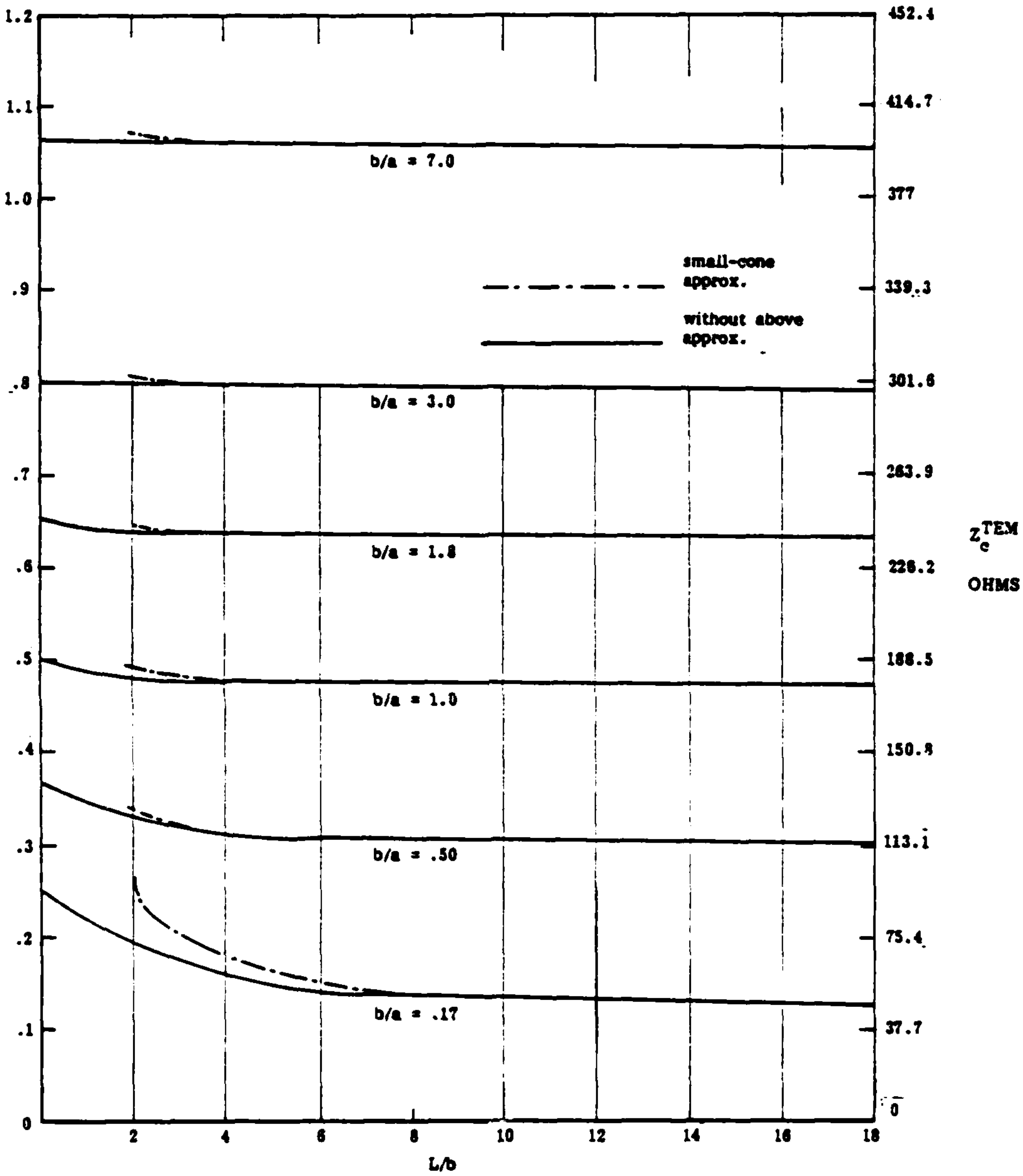

Figure A8. Characteristic impedance of two conical plates as a function of (L/b) with (b/a) as the running parameter.

NOTE. (i) $f_g = Z_c^{TEM} / (377 \text{ Ohms})$

(ii) THIS FIGURE IS REPRODUCED FROM REF. [5]

II. RELATIVE ORIENTATION OF PEAKER ARMS

In this section, we shall estimate the optimum locations of 4, 6 and 8 peakers relative to the Marx column. This is, however, an estimation that is dependent on which cross section of the Marx peaker system is under consideration, and the approach taken here is to seek the relative positions at the switch end of the Marx/peaker configuration and then let the peakers be slanted parallel to the Marx. From considerations described in earlier work [9], the requirements are that all the peakers be on an equipotential surface $u = u_o$ and that the net flux linkage between any two peakers be zero. This translates to locating the peakers (4, 6, or 8) on an equipotential $u = u_o$ (corresponding to 150 Ω) and ensuring that Δv between any two adjacent peakers is the same. In this context,

$w = u + jv \equiv$ complex potential
$u \equiv$ equielectric potential or magnetic field lines
$v \equiv$ equimagnetic potential or electric field lines

The conformal transformation from the physical z plane to the complex potential w plane for a single conductor representing the Marx is shown in Figure A10. The procedure for determining the peaker location is summarized below.

i) Choose the number of peakers $N_P = 4, 6, 8$

ii) Choose the equipotential $u = u_o$ on which all of the N_P peakers can be located such that this particular equipotential corresponds to a nominal 150 Ω impedance.

iii) Determine $v_1, v_2, \ldots v_{N_P}$ such that any Δv between adjacent peaker arms is the same.

In step (iii) above, the intersection of the $v_1, v_2, \ldots v_{N_P}$ lines with $u = u_o$ surface determines the location of the N_P peakers. However, there is an arbitrariness in the starting location, i.e., having chosen v_1, the locations of the remaining $v_{(N_P - 1)}$ peakers are uniquely determined.

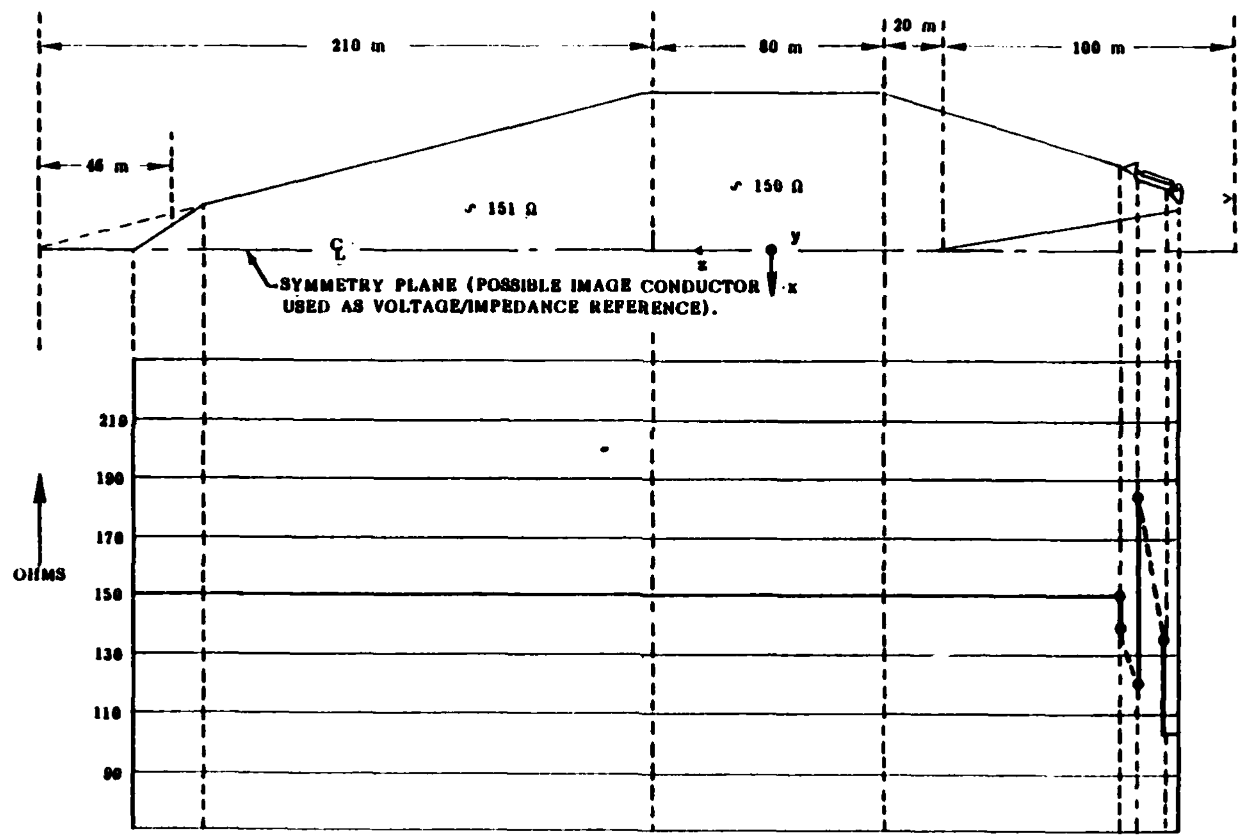

Figure A9. Impedance profile along the symmetry axis (x=0) of Atlas 1 (TRESTLE).

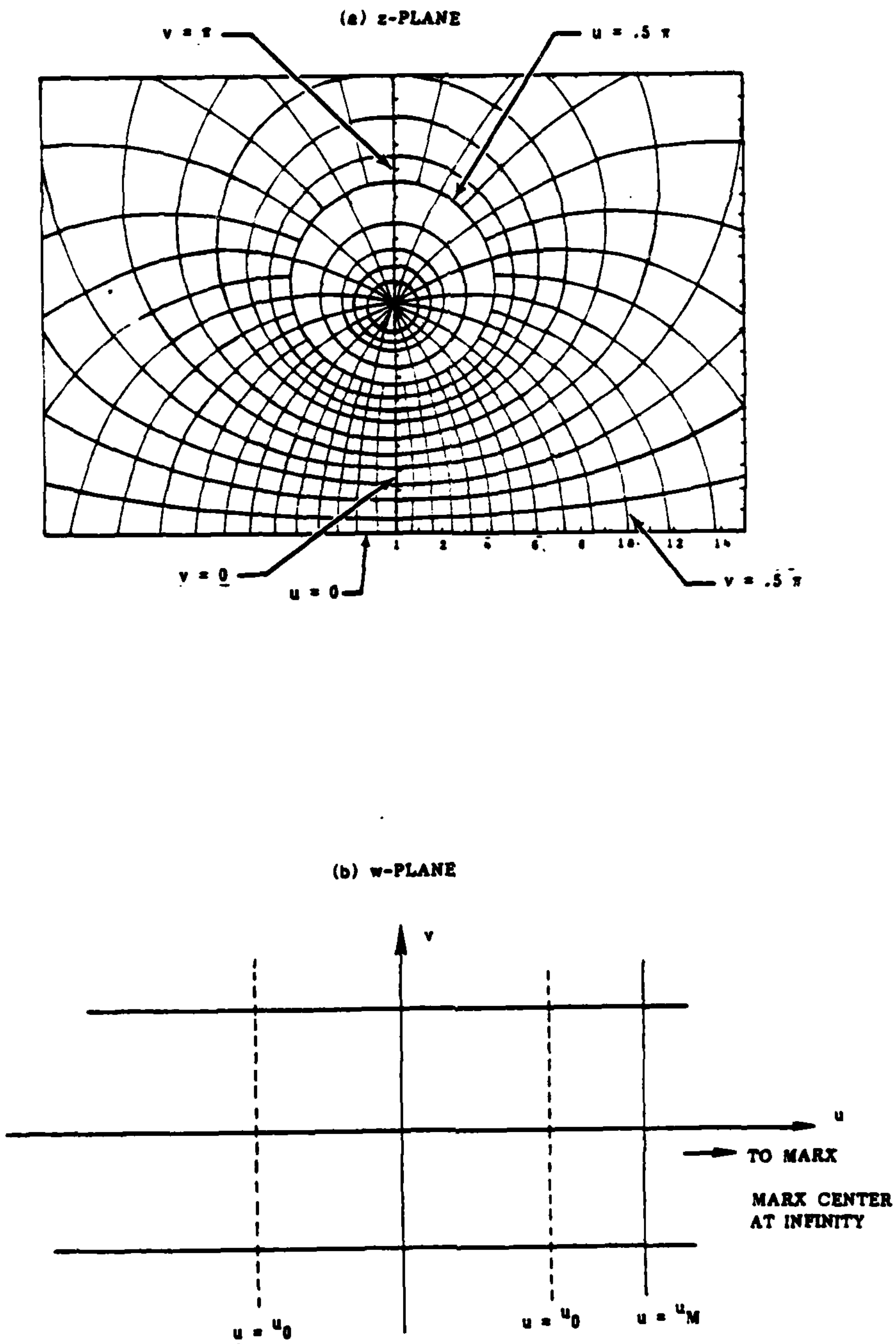

Figure A10. Conformal transformation of a single conductor (Marx column) above a ground plane.

In Figure A10a, the constant u and constant v lines are shown for a line charge or line current. Since the Marx column is modelled by an equivalent conductor with a diameter of about 0.5 m, it is seen to be a circle represented by $u = u_M$ where u_M is the Marx potential. This is also seen in the w-plane diagram of Figure A10b. $u = u_o$ is indicated in Figure A10b corresponding to the nominal impedance value of 150 Ω. Now, at least mathematically, the problem reduces to determining $v_1, v_2, \ldots v_{N_p}$ unknowns. It is noted that while choosing $u = u_o$ implicitly the peakers are assumed to be line charges as well. Because of their finite sizes, the required equipotential surface will deviate from the nominal $u = u_o$ value. However, given the mechanical considerations and the inevitable experimental optimization of locations, we ignore this effect for the present and only seek an approximate starting location for the peakers in the experimental optimization process.

Under the approximations stated above, u_o is determined as follows.

$$f_p = \frac{Z_L}{Z_o} = \frac{150\ \Omega}{377\ \Omega} = 0.3978 = \frac{u_o}{2\pi} \tag{8}$$

Equation (8) yields

$$u_o = 0.795\ \pi \tag{9}$$

which is easily located in Figure A10a to be the equipotential surface on which the N_p peakers should be located. Having chosen the particular equipotential constant Δv between adjacent peakers implies that

$$\Delta v = 2\pi/N_p \tag{10}$$

The accompanying Table A1 lists the v_n for $n = 1, \ldots, N_p$ where one of the v_n (say, v_1) is chosen arbitrarily, to be the starting value. Symmetry is preserved.

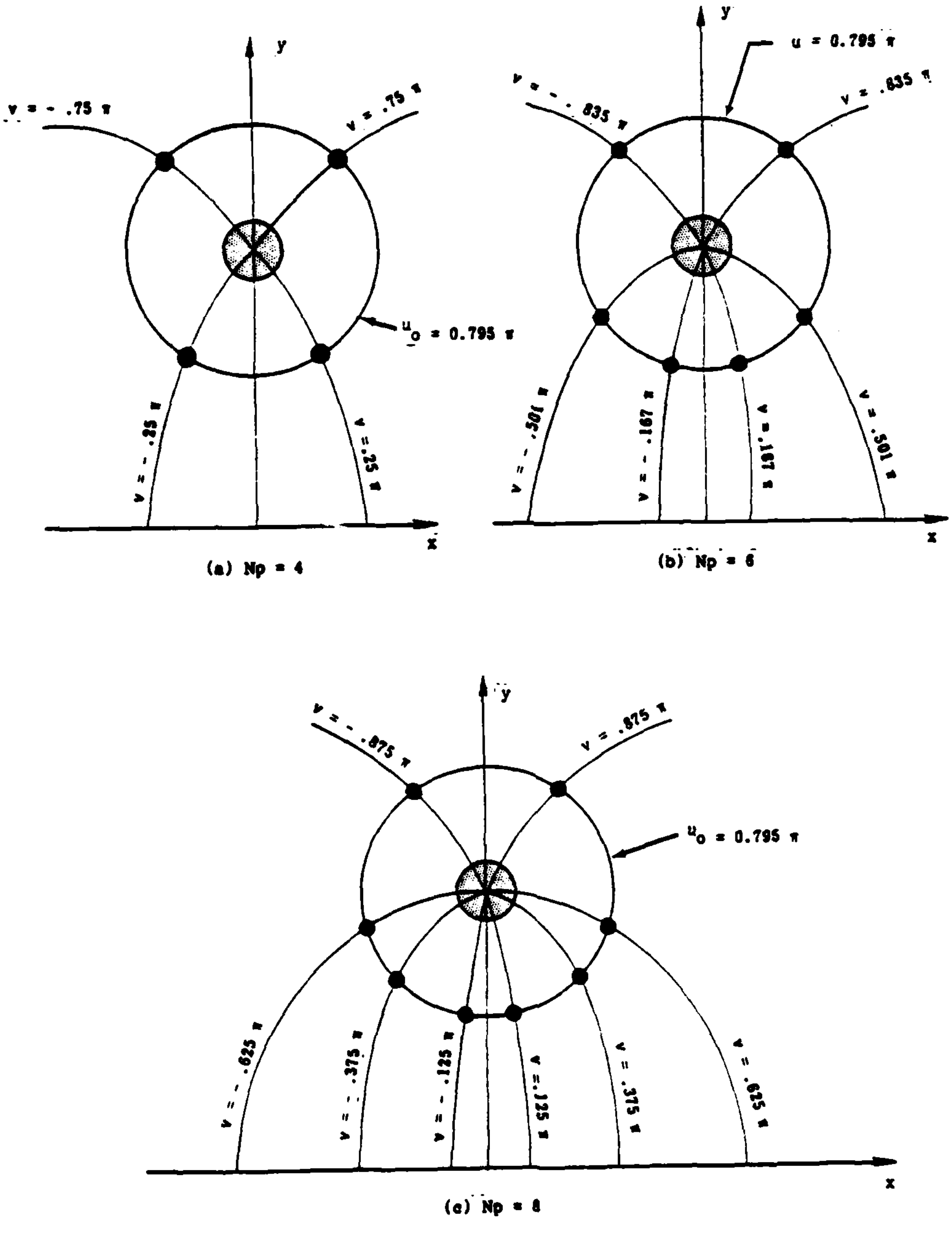

Figure A11. Relative orientation of 4, 6, and 9 peakers for a pulse impedance of 150 OHMs.

The above values are schematically shown in Figures A11a, b, and c, respectively for $N_P = 4, 6,$ and 8. It is observed that the Table A1 values are yet to be unnormalized since all physical distances are normalized such that the Marx ("line current") is located at (0, +1). In the remaining part of this effort, we shall be computing the coordinates of the centers of peakers

$$(x_i, y_i); \; i = 1, 2, \dots N_P$$

for a given set of values of N_P, r_M, (x_M, y_M). This procedure simply involves taking the Table 1 values and denormalizing them. The cases to be studied are:

Case 1	Case 2	Case 3
$N_P = 4$	$N_P = 6$	$N_P = 8$
$r_M \equiv$ radius of Marx = 25 cm	$r_M = 25$ cm	$r_M = 25$ cm
$(x_M, y_M) = (0, 1.2\text{m})$	$(x_M, y_M) = (0, 1.2\text{m})$	$(x_M, y_M) = (0, 1.2\text{m})$

In each case above, (x_i, y_i) for $i = 1, 2, \dots N_P$ will be tabulated, which will serve as the starting value for the locations of the peakers in an optimization process that is best accomplished experimentally.

TABLE A1. NORMALIZED PARAMETRIC VALUES THAT UNIQUELY LOCATE A GIVEN NUMBER OF PEAKERS (N_p) AT THEIR NEAR-OPTIMAL POSITIONS.

N_p	u_o	Δv	$v_1, v_2, \ldots v_{N_p}$
4	0.795π	0.5π	-0.75π, -0.25π, 0.25π, 0.75π
6	0.795π	0.334π	-0.835π, -0.501π, -0.167π, 0.167π, 0.501π, 0.835π
8	0.795π	0.25π	-0.87π, -0.625π, -0.375π, -0.125π, 0.125π, 03.75π, 0.625π, 0.875π

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[2] D.V. Giri, "A Study of the Monocone Switch Used With Marx Pulsers", ATLAS Memo 26, 28 September 1979.

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[5] F.C. Yang and K.S.H. Lee, "Impedance of a Two-Conical Plate Transmission Line", Sensor and Simulation Note 221, November 1976.

[6] F.C. Yang and L. Marin, "Field Distributions on a Two-Conical Plate and a Curved Cylindrical Plate Transmission Line", Sensor and Simulation Note 229, September 1977.

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[9] D.V. Giri and F.R. Graham, "Electromagnetic Characterization of a Marx Pulse Generator", AFWL-TR-81-31, Air Force Weapons Laboratory, Kirtland Air Force Base, August 1981.

APPENDIX B

TRESTLE PULSER UPGRADE SUPPORT EXPERIMENTS

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I. BACKGROUND

Historically, when the problems with the TRESTLE output waveform became apparent, an analysis of the problem began at Maxwell Laboratories, Inc. (MLI) and BDM. At MLI the analysis addressed two effects, the prepulse and the notch in the waveform. We felt initially that the pulser could be modelled in detail with existing circuit codes.

The prepulse was measured to be larger than expected. Both modelling and analysis of the waveform indicated a prepulse due to the erection of the Marx generator. Because of the capacitive coupling between the Marx and the peaker arms, the electric field generated by the Marx erection drives displacement current into the simulator.

The initial hypothesis was that the notch was caused by the peaking capacitance value was too small, either due to a resonance in the capacitor or an incorrect value due to an over simplification of the circuit during the design of the system. As the analysis and the experiments proceeded, it became apparent that there were other effects involved. While the notch could be reproduced qualitatively by the analysis, the waveform could not be reproduced in detail without varying parameters and adding a radiation resistance element to the model. At the time it was felt that there were other effects which were compounding the problem. Subsequent studies by BDM concluded the effective value of the peaking capacitance was only 60% of the stated value and that this was the primary cause of the notch.

Since the same peaking capacitor design was used in other MLI pulsers (TORUS) without producing the notch, it is likely that other effects are aggravating the problem. The differences between TORUS and TRESTLE are the length of the peaking arms, the pulser symmetry and the capacitance value. Basically, the TORUS design (bicone) is much superior in a geometric sense in launching waves onto a simulator.

II. TEST PLAN

Before any decision can be made on a pulser upgrade (both near and far term) a better understanding of the problem is required.

Detailed data on the pulser operation is required so that we can establish whether the mathematical models actually agree with the experiment or whether the fit has been forced by tweaking parameters.

The areas that need further investigation are:

1) The unbalanced charging and discharging of the peaker arms due to the enhanced current at the edge. This would lead to resonances which are not included in the simple analysis.

2) The propagation of the fast wave through the peaking capacitor structure. Aside from diffraction problems caused by the switch orientation, the peaker arms affect the propagation by virtue of field boundary conditions at the peaker arms. Above a resonance, the TEM mode is cut off and is attenuated while higher order modes are generated. This could degrade the risetime and may aggravate the notch.

3) The discontinuity at the section where the transition from the pulser to the simulator may cause reflections. Early tests at MLI indicate a somewhat surprisingly large reflection from this region.

The best way to acquire the required data would be to inject a fast rising low-level pulse into the switch and map the fields and currents in the pulser region. Since this may be impossible due to the level of effort of the present contract and the operational status of the simulator, a second approach will probably be necessary.

It should be possible to make measurements in place which will give nearly the same information as the low level measurement. Measuring the following quantities could help the analysis of the problem:

a) The currents in each of the four peaker arms and the Marx at the transition region.

b) The output switch current

c) The electric field on the center line of the simulator near the switch and near the transmission.

d) The field approximately halfway down the conical launching section to the simulator volume.

e) If possible, the current in the peaking arms and the Marx at the switch end would be useful.

From these measurements it should be possible to determine the accuracy of the existing analytical models of the TRESTLE pulser.

III. PROGRAM OBJECTIVES

At present, the only aspects of the pulser that can be improved, in the near term, appear to be those related to the peaking capacitor performance. Alternate designs are available for the peaking arms which would push the resonance to >100 MHz. In addition, some rearrangement of the peaking arms may be possible within the existing volume. The outcome of the present program would be to establish the magnitude of the gains that might be made.

It appears that reducing the prepulse and improving the wave properties of the structure (other than those related to peaker improvements) could not be made without major hardware changes. If there were to be a major hardware change, a shorter, or perhaps lumped peaking capacitor design should be considered.

APPENDIX C

TRESTLE PULSER IMPROVEMENT STUDY

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TRESTLE PULSER IMPROVEMENT STUDY

Physics International Company (PI) has reviewed the supplied reference material and attended meetings at LuTech on 8 August 1980 and at the AFWL on 1 October 1980. At the 1 October meeting at the AFWL, the TRESTLE site was visited to examine the pulsers and to view the existing physical configuration of the TRESTLE pulser/transmission line interface.

The following report includes:

1. The PI evaluation of the present TRESTLE pulser operation and analysis of the causes for non-ideal pulser output,

2. Recommendations of tests that could be performed to confirm the correctness of the analysis,

3. Possible improvements to the TRESTLE pulsers should the analysis prove correct,

4. Rough cost estimates and schedules to effect some of the tests and recommended improvements.

The report constitutes the PI input to the TRESTLE Pulser Improvement Study and is a result of reviewing the supplied reference material, discussions with the contractor (MRC), AFWL and other sub-contractors at the 8 August and 1 October meetings.

I. EVALUATION AND ANALYSIS OF THE PRESENT TRESTLE PULSER OPERATION

The time domain output pulse of the TRESTLE pulser exhibits the following waveform distortions:

1. Excessive prepulse
2. Risetime after prepulse longer than desired
3. Notch after peak voltage

The risetime deficiency is apparent when both pulsers fire in synchronism and is further distorted depending on the amount of time asynchronism of the two pulsers. Presently, asynchronism is less than 10^{-8} seconds for 80% of all system shots.

The TRESTLE pulser is a dynamic peaking capacitor circuit. The idea of a dynamic peaking capacitor circuit is to precharge the Marx inductance to the required output current and then to fire the output switch so that the resultant risetime into the load (transmission line) is not limited by the Marx inductance. If the peaking capacitance is the proper value, and the output switch closes at the proper time, the desired double exponential waveform is produced.

The peaking capacitor must be of exceptionally high quality since the wave launched by the firing of the output switch must traverse the peaking capacitor structure. In the TRESTLE pulser a distributed peaking capacitor is used, i.e., the peaking capacitor is configured as part of the transmission line so that the peaking capacitor can be physically long to withstand the 5 MV required output voltage.

An idealized peaking capacitor circuit is depicted in Figure C1. The circuit values used are those for the TRESTLE pulser as given on Page 8 of Reference [5] supplied by MRC, except for the load inductance (1 μH), which was adjusted to give an output risetime of 14.7 ns for illustrative purposes. The Marx charge voltage is 1 volt.

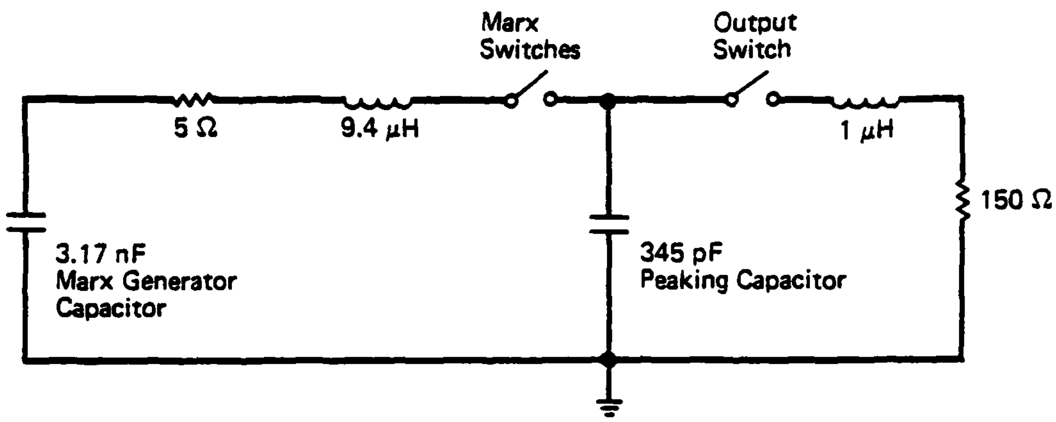

Figure C1. Idealized TRESTLE peaking capacitor circuit.

Figure C2 is the resulting output pulse when the output switch is closed at 85 ns (at approximate peak current). The resulting risetime is about 13.7 ns (10-90). The risetime is thus shortened from the theoretical L/R risetime by the fall of voltage after peak. The waveform closely approximates the desired double exponential as further illustrated in Figure C3, which depicts the same conditions on a "longer sweep". Note the relative output voltage is about 0.94 volts.

Figure C4 illustrates the output of the same circuit when the output switch is closed at 40 ns. This case resembles the 40 ns case of the actual pulser illustrated in TRETM-13, Page 13-14(a). The risetime is about 85 ns and the relative output voltage is about 0.9 volts. Figure C5 is a "long sweep" version of the 40 ns firing time. A double exponential pulse results with a very long risetime. The Marx inductance is not precharged to the correct current.

Figure C6 illustrates the output waveform from the ideal circuit when the output switch is fired at 130 ns. The risetime has been shortened to 10 ns (10-90) by the rapid fall of volts after peak. The peak output voltage is 1.35 volts (relative to a 1 volt Marx charge). Figure C7 is a "long sweep" version of Figure C6. This resembles the 120 ns case shown on Page 13-14(d) of TRETM-13 (actual pulser firing). Note the notch after peak voltage.

A notch after peak is thus illustrated even on an ideal circuit when the output switch is fired well after peak current has occurred.

It is well to note that the notch occurs somewhat earlier in the actual pulser waveforms than on the idealized waveform (Figures C6 and C7). The earlier occurrence of the notch in the actual waveforms would result in the case where the load impedance is lower than 150 Ω, which was the case at the PTF where the tests were performed. In addition, Ian Smith (Preliminary Comments on TRESTLE Pulser, August 1980) estimates the peaking capacitance is actually lower than indicated in Figure C1.

Determining the proper firing time for a distributed peaking capacitor circuit with long peaking capacitors is difficult. Since the peaking capacitor has about a 15 ns transit time (or longer), current is flowing into the peaking capacitor (from

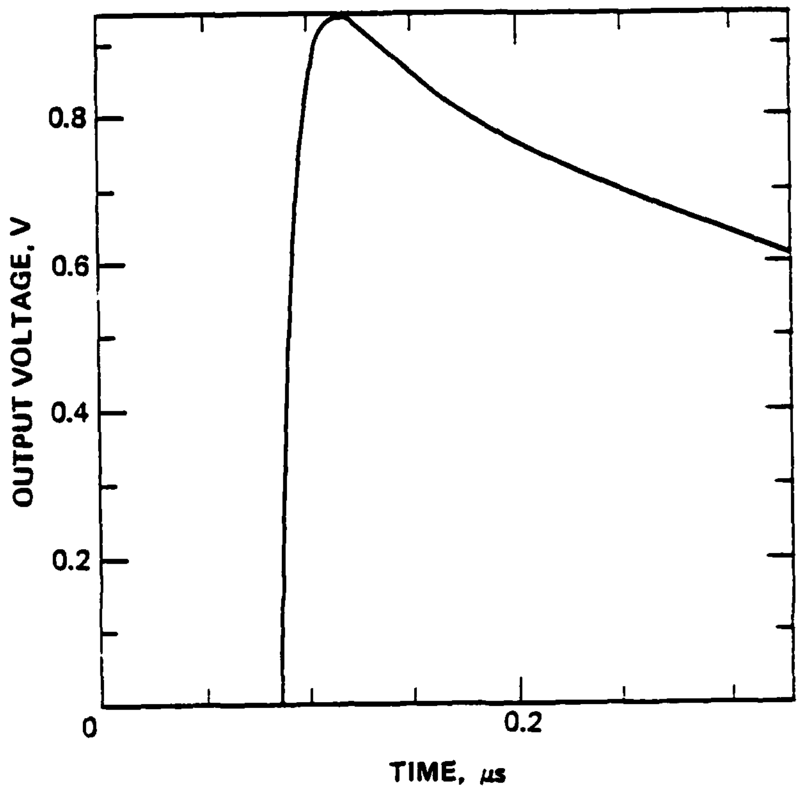

Figure C2. 85 ns Output switch firing time.

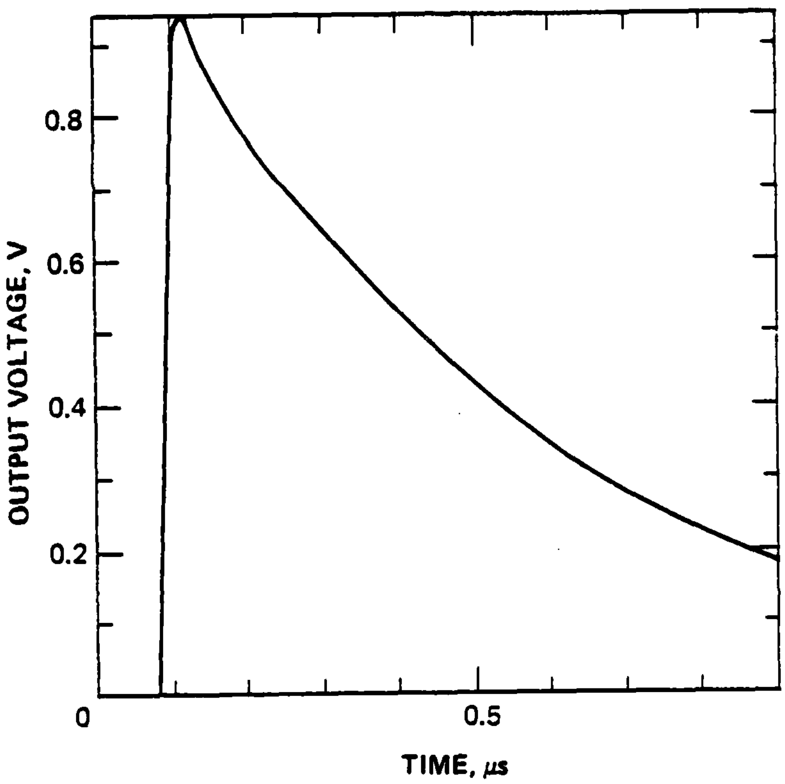

Figure C3. 85 ns Firing time, long sweep.

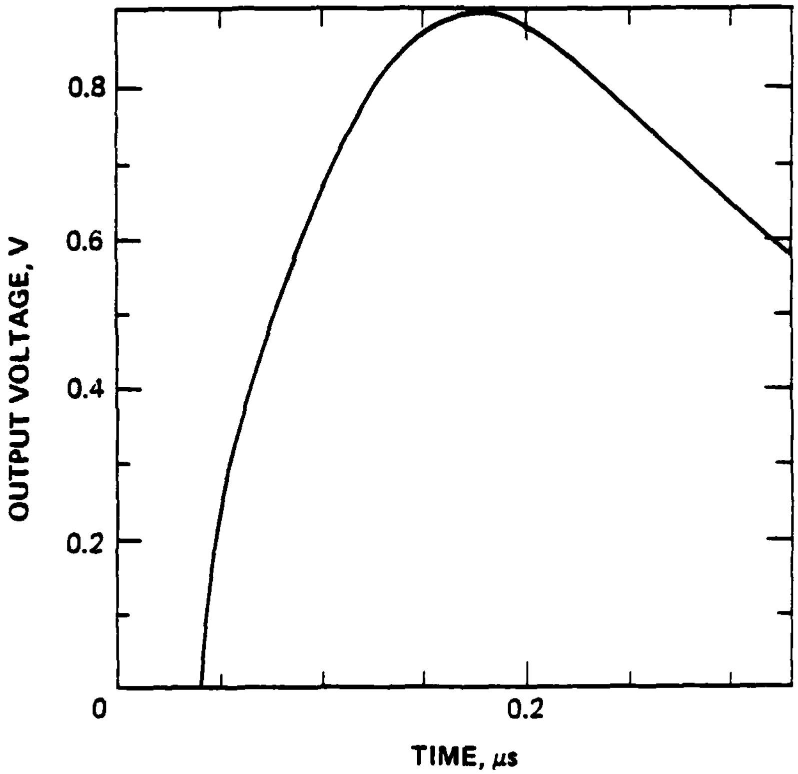

Figure C4. 40 ns Output switch firing time.

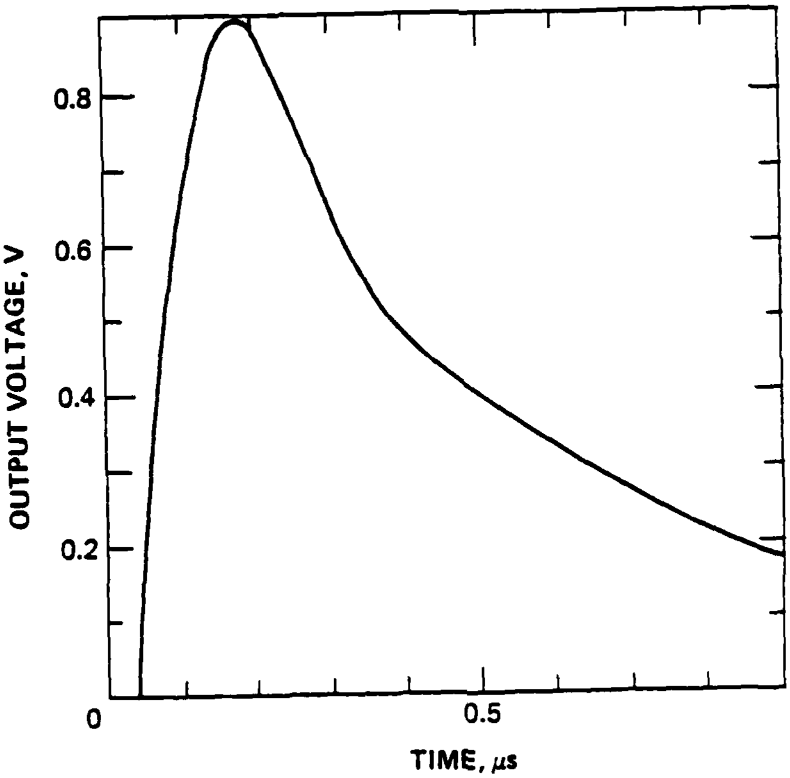

Figure C5. 40 ns Firing time, long sweep.

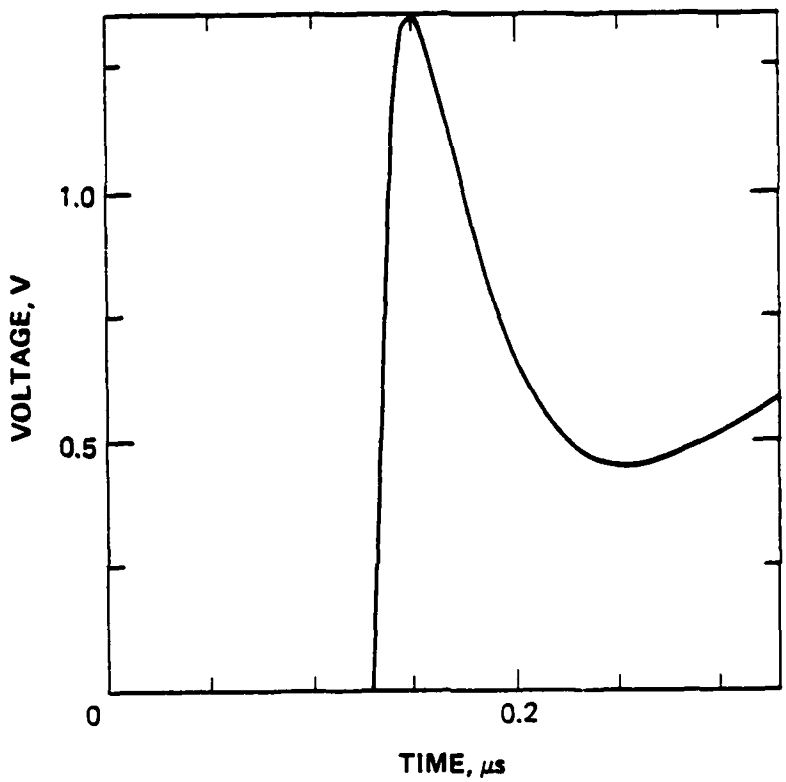

Figure C6. 130 ns Output switch firing time.

the Marx) for similar times ($\backsim$ 15 ns) after the main switch is closed before the arrival of the output wave at the end of the peaking capacitor. This time is about 18% of the peaking capacitor charge time. It is desirable that the Marx be near peak current when the wave leaves the end of the peaking capacitor.

In a distributed peaking capacitor circuit, the peaking capacitor forms the initial part of the transmission line and, therefore, has a distributed capacitance. This distributed capacitance is charged (in a distributed manner) as the peaking capacitor is charged and, therefore, contributes to the prepulse in the same way as the output switch stray capacitance (the major source of prepulse in non-distributed peaking capacitor circuits). Therefore, the distributed capacitance is proportional to the length of the peaking capacitor and the prepulse is larger for long peaking capacitors.

The risetime that can be propagated through the peaking capacitors depends on the quality of the peaking capacitors. Ideally the peaking capacitors should have:

1. Low wave impedance when considering the windings as transmission lines

2. Short pulse time

3. Low equivalent inductance

References [5-8] give the pad impedance of the peaking capacitor as 0.14 Ω. This translates to $\backsim$ 24 Ω pulse impedance for the entire peaking capacitor assembly.

The pulse time is given as 7.9 ns and the equivalent inductance extrapolates to 152 nH.

Additionally, the peaking capacitor must resemble the transmission line in configuration since it forms the "wave launcher" connecting the switch to the transmission line.

An equivalent circuit for the TRESTLE pulser was developed that considered the peaking capacitors as transmission lines as described in Reference [5-8]. The equivalent circuit is shown in Figure C8. The peaking capacitor pads were divided into six equivalent 4 Ω transmission lines separated by 3 ns sections of 150 Ω transmission lines to simulate the distributed character of the peaking capacitors. Figure C9 shows the resultant output voltage waveform and compares the output with an equivalent ideal lumped peaking capacitor voltage output. The ideal circuit shows no prepulse since switch capacitance was not included in either circuit model. The distributed peaking capacitance model shows an 18% prepulse. The risetime of the ideal circuit shows a 12.8 ns risetime (due to the included switch inductance). The distributed peaking capacitance circuit shows the output pulse delayed by the transit time of the peaking capacitor and the risetime is increased to 25 ns due to the pulse impedance and transit time effects of the distributed peaking capacitor elements. The slight ripples in waveform of the distributed peaking capacitor are due to these transit time effects. Both circuit models had identical output switch firing times.

The model was expanded to include inductance in the peaking capacitor elements as suggested in References [5-8]. The circuit model is shown in Figure C10 and the resulting voltage output waveform is shown in Figure C11. Figure C11 is shown on an expanded time scale so that the full prepulse can be observed. The risetime of the inductive peaking capacitor model is 27 ns and the prepulse is about 13%. Thus, adding inductance to the peaking capacitors only slightly degraded the performance from the non-inductive case.

It should be emphasized that these circuit models do not include switch stray capacitance as they were developed to show the effects of distributed peaking capacitors with elements having significant transit time and the prepulse effects would be masked by including switch capacitance. The actual TRESTLE prepulse is larger due to switch stray capacitance.

The presence of the Marx generator and the rather large transition section between the pulser and the transmission line could affect the degradation of risetime as the pulse leaves the pulser and propagates into the TRESTLE test volume. In TRESTLE, the transition section houses the Marx trigger generator. A

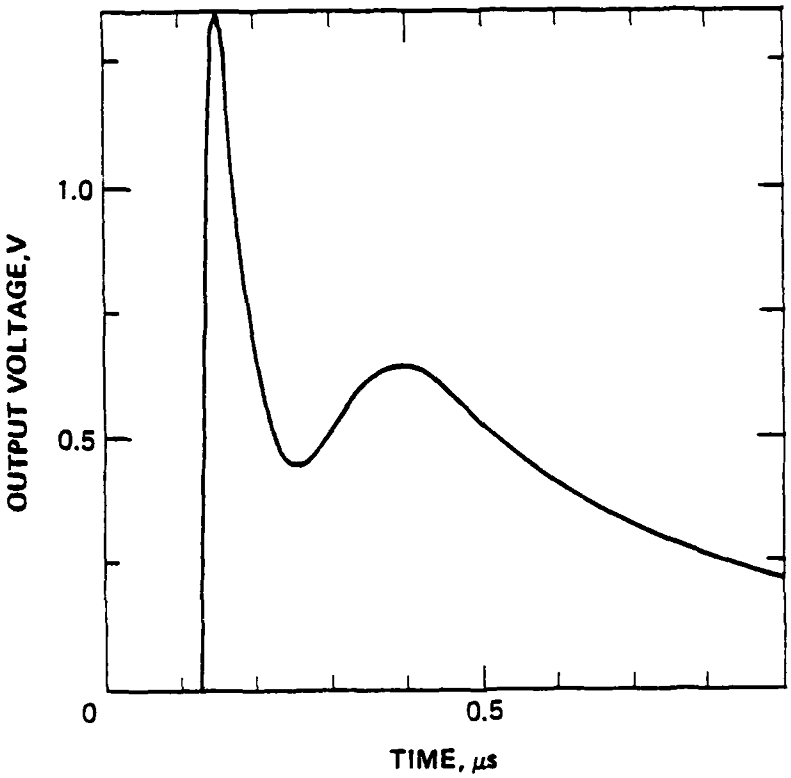

Figure C7. 130 ns Firing time, long sweep.

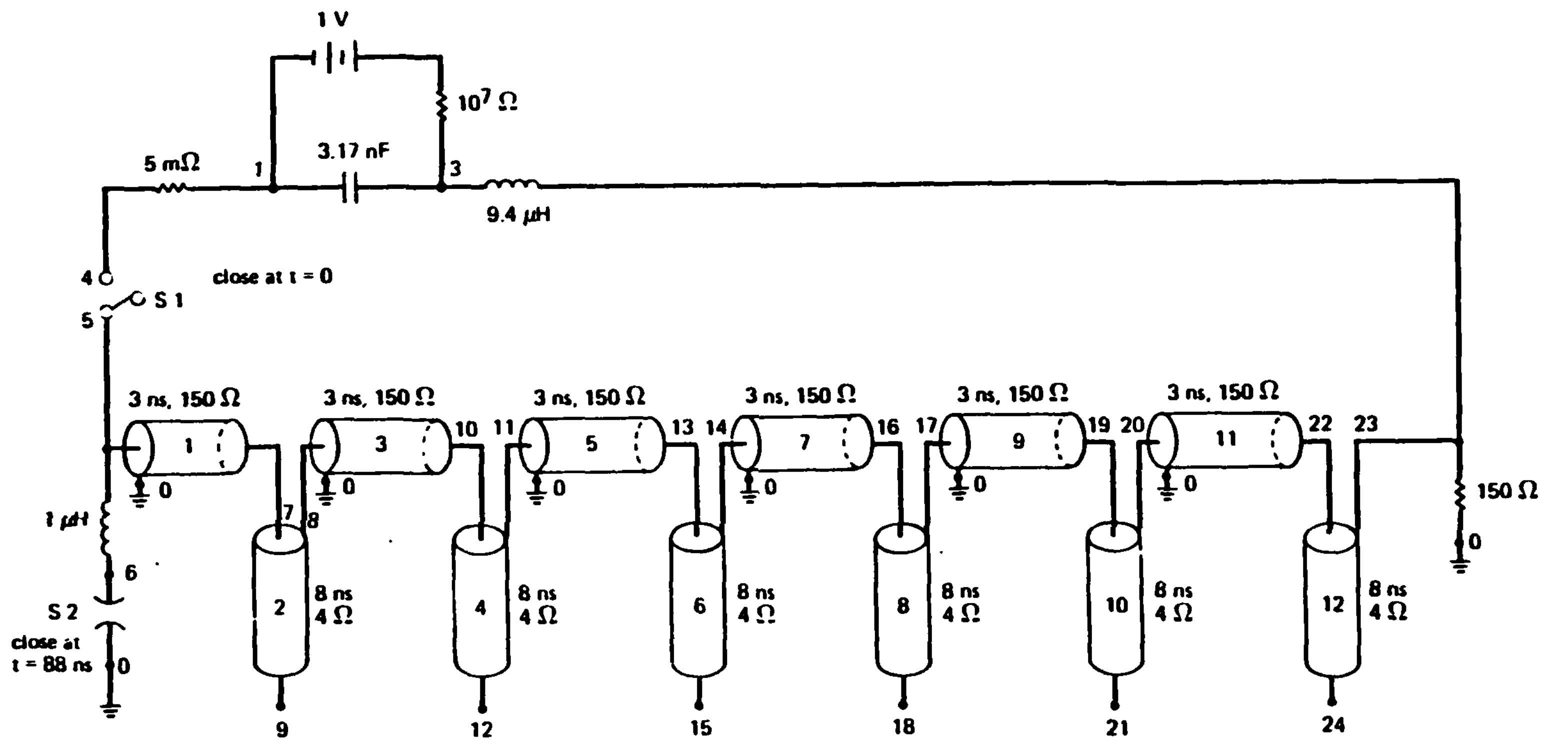

Figure C8. TRESTLE Marx and peaking circuit.

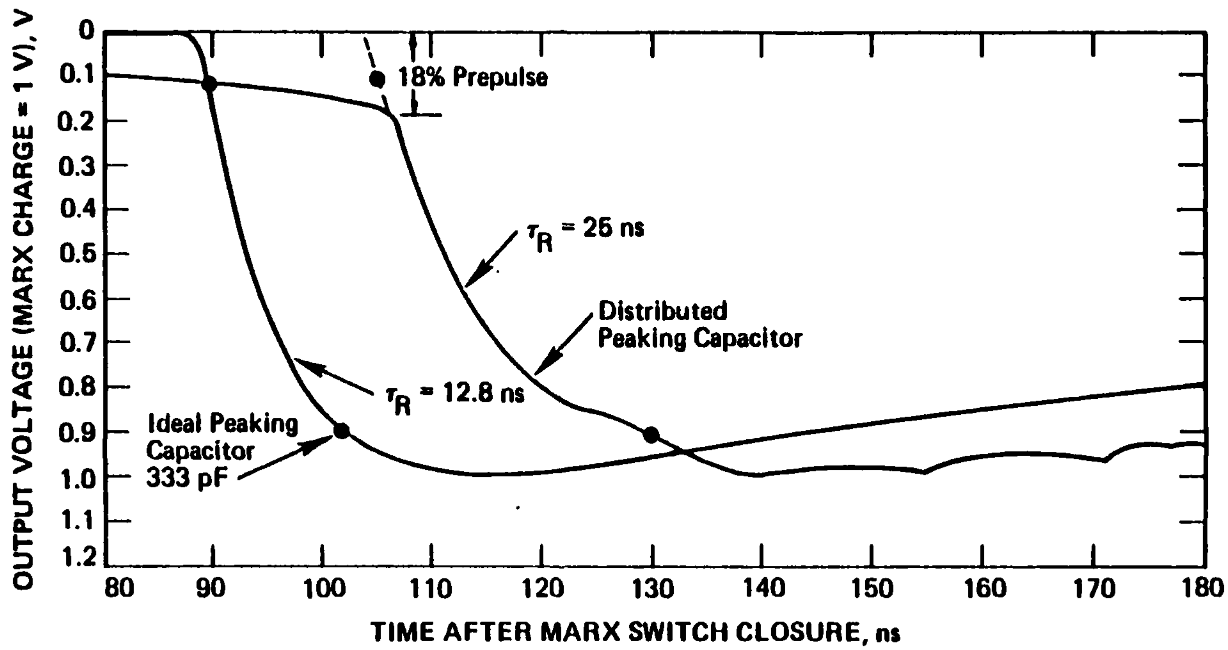

Figure C9. TRESTLE model output waveforms.

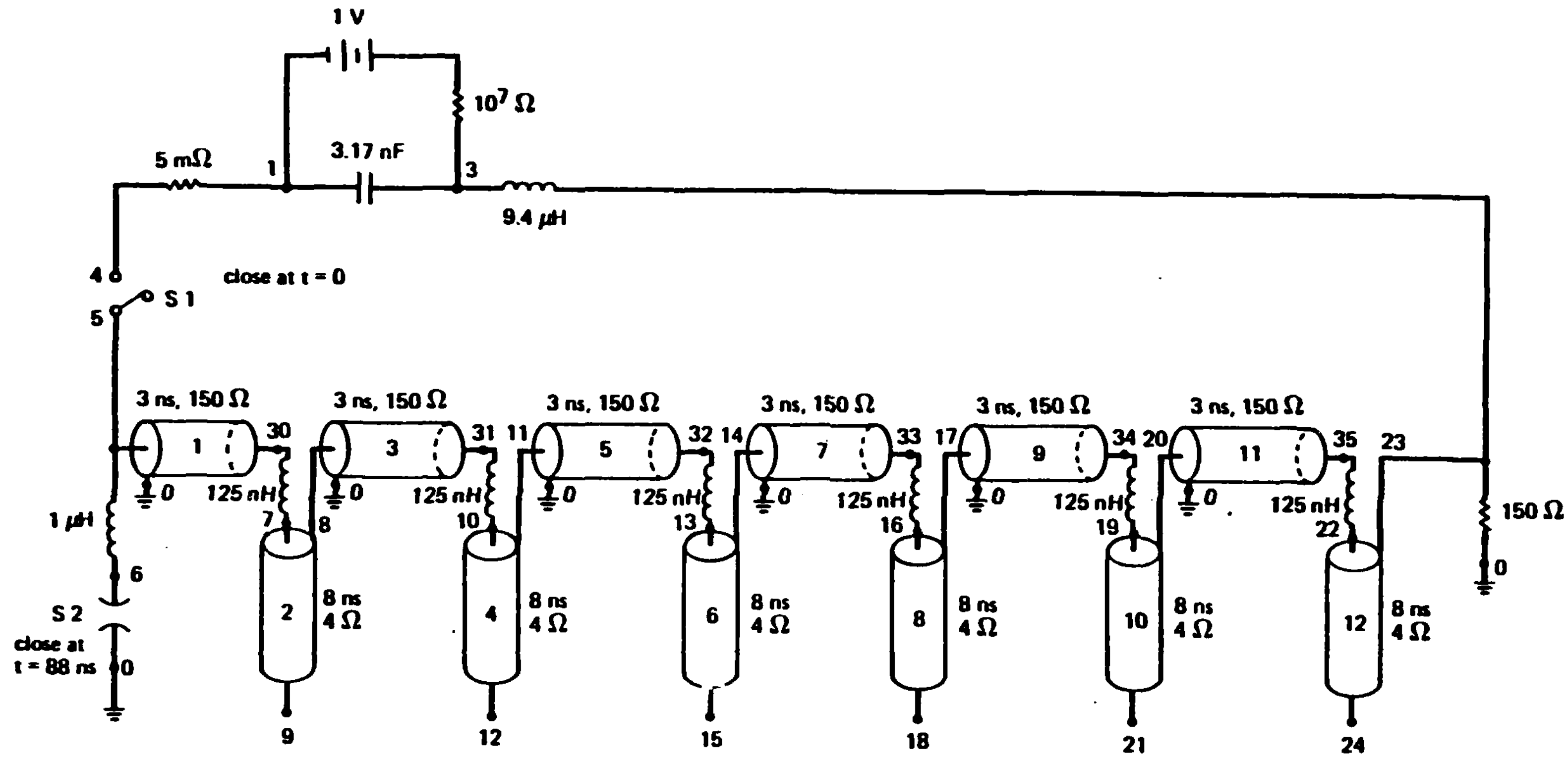

Figure C10. TRESTLE Marx and peaking circuit.

parallel plate transmission line with a conical input section, such as TRESTLE, establishes fields at the edges and on the outside of the transmission line, as well as inside the transmission line as the wave propagates down the transmission line into the test volume. The sum of all these fields results in the characteristic impedance of the transmission line. Electrically reflective disturbances, such as the Marx generators and the transition section, can disturb the fields on the outside of the transmission line by reflecting high frequency components of the wave back toward the main output switch. Such reflections were observed from the transition section during the PTF Low Voltage Spring Tests (References [5-8]). The effect of such reflections is to strip the high frequencies from the propagating wave (on the "backside" of the conic transition) requiring energy to be extracted from the test volume side of the transmission line plate to establish these fields on the "backside" of the transmission line. The effect is possibly a progressive degradation of the risetime as the wave propagates into the test volume. Progressive degradation of the risetime is observed in TRESTLE and was observed at PTF.

To summarize the findings of this study:

- The prepulse is caused by the distributed stray capacitance of the peaking capacitors and the switch stray capacitance coupled with the rapid rate of charge of these stray capacitances by the peaking capacitor circuit.

- The slow risetime is caused by the construction and positioning of the peaking capacitors. The progressive slowing of the risetime, as measured in the transition sections and into the test volume, may be caused by the poor geometry (from a pulse propagation viewpoint) in the region of the pulsers and the pulser to transmission line transition. The risetime in the test volume is further degraded by asynchronism in the firing of the two pulser main output switches (Marx jitter plus switch jitter).

- The notch after peak is caused (at least to some extent) by late firing of the main output switch probably in an attempt to improve the risetime performance. The geometry of the pulsers and the peaking capacitors and a low peaking capacitance could also contribute to the notch.

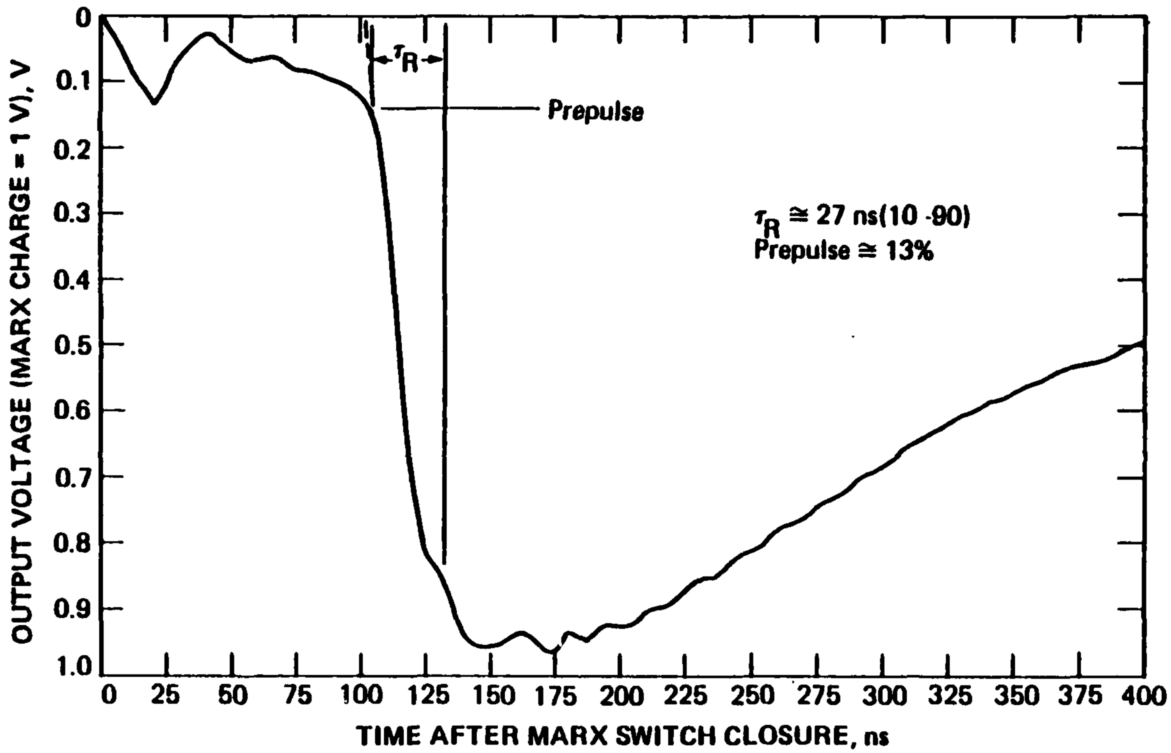

Figure C11. TRESTLE model output waveform.

II. RECOMMENDED TESTS TO CONFIRM ANALYSIS

Low level tests can be performed that will confirm the postulate that the peaking capacitors and the peaking capacitor geometry cause essentially all of the individual pulser waveform deficiencies.

The tests require the existence of a pulse generator with a very fast risetime and a "clean" output pulse waveform. Many pulse generators (or trigger generators) exist that would be suitable. For example, a square wave generator or a double exponential pulse generator delivering $\backsim$ 100 kV pulse into a 50 Ω cable would be suitable. The pulse could be injected at the main switch location and possibly even though the main switch electrodes.

The following tests should be performed -- not necessarily in the order listed, as all the tests would be useful.

1. A tapered metal plate should be placed in the position of the peaking capacitors in a manner so as to short out the peaking capacitors and to complete a "smooth" transition between the peaking capacitors and the pulser to transmission line transition. Pulses should then be injected at the main switch location.

This test would confirm the ability of the transmission line conic section to support a fast risetime pulse into the conic transition section. Measurements should be made at several positions along the conic transition section to observe any progressive deterioration of the risetime as the pulse propagates down the transmission line. Reflections should be observed at the switch location in order to determine the position of propagation disturbances.

More sensitive monitors may be required to provide sufficient signal to noise ratio at the monitor positions.

During the course of this test, conductors could be added to provide conduction of the pulse around the Marx generator and pulser to transmission line transition section in order to provide information relative to "back of the line" wave launch problems as described in the previous section.

2. Cover the peaking capacitor with conductive foil. For this test, the peaking capacitors should be shorted out by covering them with aluminum foil. Then pulses should be injected at the output switch position. This test would determine the suitability of the peaking capacitors as configured to pass the propagating wave into the test volume.

The same pulser and diagnostics are required to perform this test as in Test 1.

Conductive tubes could be placed at the sides and/or behind the Marx generator to test the effect of improved "back line" propagation on the risetime in the transition region of the transmission line.

3. Repeat Test 2 with the peaking capacitors unshorted and in the original configuration.

This test will determine the suitability of the peaking capacitors as a wave launcher. Additional peaking capacitors would be necessary to bypass the back side of the Marx for back line propagation measurements.

4. Add peaking capacitance. This test would determine the beneficial effects of added peaking capacitance to improve the wave launch capability of the peaking capacitors. By temporary placement of the additional peaking capacitors, various configurations of the peaking capacitors could be evaluated.

5. A facility such as ALECS could be used to test the effect of "back of the line" perturbations on the pulse propagation characteristics in the test volume.

Large conducting perturbations such as foil covered wooden structures could be placed on top of the ALECS conic transition and a test pulse injected to evaluate the deleterious effects of such perturbations on the risetime of the injected pulse in the test volume.

Evaluation of the results of Tests 1 through 5 would be used to guide modifications to the TRESTLE pulser modules to improve performance.

III. POSSIBLE IMPROVEMENTS TO THE TRESTLE PULSERS

Assuming that the previously described tests are performed and confirm that additional peaking capacitors and proper placement of the additional peaking capacitors will improve the TRESTLE pulser performance, this improvement should be effected. In addition to improving the risetime, reducing the notch after voltage peak, and improving "back of the line" propagation performance, additional peaking capacitance should reduce prepulse due to slowing down the rate of change of voltage on the peaking capacitors.

Shorter, high quality peaking capacitors could also replace the existing peaking capacitors. This change would require a major redesign of the pulser configuration and the pulser dielectric gas housing.

PI manufactures a very high quality peaking capacitor for the TEMPS type of horizontally polarized radiating simulators. A 5 MV version of this peaking capacitor would be $\sim$ 1.5 M in length and has a diameter of about 40 cm for a 75 pf unit. Parallel peaking capacitors of the TEMPS design, sufficient to replace the present TRESTLE peaking capacitors, would provide a very low impedance wave launch peaking capacitor with only 1.5 ns pulse transit time. Such a change would require placing the peaking capacitors well away from the Marx generator so that the prepulse would be reduced by both increased loop inductance and less peaking capacitor stray capacitance to ground.

To reduce asynchronism in firing of the output switch, Marx jitter could be reduced by adding UV illumination to the Marx switches and the output switch jitter could be similarly reduced (by adding UV illumination).

IV. ROUGH COST ESTIMATES AND SCHEDULES FOR TESTS AND PULSER IMPROVEMENTS

Each of the tests described in Section II could be performed with about 1 to 3 man months effort by one engineer and two technicians (one to three weeks per test). Assuming Albuquerque based personnel and the availability of the required equipment, the average test would cost about \$15K to \$20K. A concentrated effort to perform several tests sequentially could cost less per test. These costs do not account for facility down time and down time for the facility's regular employees or special data acquisition system costs.

AFWL has recently purchased additional peaking capacitors of the original TRESTLE design and, therefore, these costs should be well known to the AFWL. The cost of the mounting of the additional peaking capacitors on the TRESTLE pulsers depends on the final geometry chosen and the complexity of the changes required, but this type of modification should be straightforward.

Installation of TEMPS type peaking capacitors would require reconfiguring and reconstruction of the entire pulser module, as the Marx generator would have to be moved away from the peaking capacitor location in order to avoid voltage flashover between the Marx generator and the peaking capacitors. The present peaking capacitors are as long as the Marx generator and, therefore, any voltage gradient between the Marx and peaking capacitor is minimized.

If shorter peaking capacitors are considered as a viable solution, a separate study should be performed and the new system modelled on the computer and also physically modelled at some facility such as PTF.

The cost of the study and development program are beyond the scope of this study. However, a complete set of TEMPS peaking capacitors for the TRESTLE pulsers would cost about \$200K. Modifications required to mount the peakers and move the Marx generator would cost many times the peaking capacitor cost (perhaps as much as \$1M). This could be an expensive program if study costs and physical modification costs are included. The benefits of such a modification could be worth the investment in terms of improved simulation performance.

Adding UV to the Marx switches could cost up to $100 to $200 per switch. Adding UV to the main switch could cost $10K or more, depending on the method chosen to supply the UV illumination.

APPENDIX D

RECOMMENDED ACTIONS FOR TRESTLE UPGRADE STUDY

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San Diego, CA 92121

I. INTRODUCTION

This PATM 80-6 memorandum describes actions that will produce a marked improvement in the output pulse characteristics of the TRESTLE simulator. This work is performed by Pulsar Associates, Inc. under contract to Mission Research Corporation as part of an Air Force contract with MRC, and is a consulting effort under the direction of Mr. William S. Kehrer of the Air Force Weapons Laboratory. On 8 August, 1980, a meeting was held at LuTech Corporation to begin this effort. This meeting was attended by pulsed power engineers from Pulsar, Maxwell Laboratories, Physics International and by Mr. Ian Smith of ISI. At this meeting, Mr. Kehrer, Jeremy Stein of EG&G and Mr. Ted Morelli of the AFWL reviewed the deficiencies in the TRESTLE waveform and discussed the ground rules under which the consulting work was to be performed. Dr. Giri of LuTech described the theoretical work he had performed to attempt to identify the causes of the TRESTLE waveform problems. The consultants were then asked to submit written comments to Dr. Prewitt of MRC by 29 August, 1980 and to address the subject of near-term experiments that could be performed at the TRESTLE facility to further unravel the fundamental causes of the waveform problems. The basic ground rule set down by Mr. Kehrer and Mr. Stein was that these experiments could not interfere with or disturb the structure of the pulser since a test program is underway at TRESTLE that cannot be delayed.

For several reasons, we believe no further experiments are required at this time. The body of experimental data developed on both the individual TRESTLE pulsers and the pair of pulsers operating as installed in the facility is considerable and need not be expanded. The problems are clearly evident from the data already gathered. Similarly, the analysis done by LuTech and others is extensive and we believe identifies the cause of much of the difficulty. With the experimental data and theoretical analysis already in hand, we believe further experiments and analysis would only delay a prompt resolution of the TRESTLE problem and Pulsar recommends that any further efforts be focused on such a resolution.

The TRESTLE waveform problems are four-fold. First, a large prepulse is evident, comprising about 30% of the peak amplitude of the output pulse. Secondly, the risetime in the working volume is considerably slower than the 10 ns

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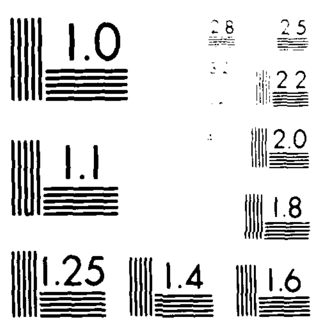

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1.6

originally specified, being instead in the range of 20 to as much as 50 ns depending on pulser aynchronism. Then, immediately following the rise of the pulser there is a deep notch in the waveform and a subsequent oscillation in the neighborhood of 4 MHz. Finally, the waveform characteristics vary substantially from shot to shot in the working volume due to lack of tight synchronism between the two pulse generators.

All four of these major deficiencies can be corrected rapidly and economically. The following sections detail Pulsar's opinion of the cause of each of these problems and the recommended cure.

II. PREPULSE

Most of the TRESTLE prepulse is caused by displacement current carried through the stray capacitance of the pulser to the ground plane as the peaking capacitors are charged. This stray capacitance is distributed along the peaking capacitor assembly and the predominant part of it is in the main output switch itself. Perhaps 10 to 25% of the prepulse is caused by "sizzle" current flowing in the main output switch prior to switch breakdown, since this assembly is an enhanced-field switch using a sharp edged electrode. More will be said about the output switch in Section IV.

Three things can be considered to reduce prepulse arising from stray capacitance. A prepulse switch can be installed at the output of the pulse generator, the stray capacitance can be reduced, or the charging time of the peaking capacitors can be increased. A prepulse switch will not work in this case, since this switch would isolate the output end of the pulser from the antenna array while the peaking capacitor is being charged. To a first approximation, this would give the peaking capacitors freedom to swing evenly at each end, one end reaching 2.5 MV below ground potential and the other end swinging 2.5 MV above ground potential, a most unsatisfactory distribution of voltage. The load is needed to force all of the peaking capacitor voltage to appear across the main switch, and in a distributed parameter pulse generator such as the TRESTLE pulser, one cannot isolate the load from the pulser with a prepulse switch for this reason.

Decreasing the stray capacitance of the TRESTLE pulser is similarly impractical. Since a large part of this capacitance is in the output switch itself (approximately 50 pF of the roughly 75 pF of stray capacitance) this would imply a smaller output switch. This in turn would raise the stress on the output switch housing and this is not a sensible tradeoff to make against prepulse if any other method is available. A Faraday screen parallel to the ground plane and tied to a remote earth ground is also unworkable for obvious reasons. Similarly, shrinking the length of the peaking capacitors to reduce stray capacitance is not advisable from the standpoint of pulser reliability. Fortunately, another course of action is available.

Pulsar recommends that the charging time of the peaking capacitor array be slowed. The prepulse amplitude will fall in proportion to the resonant frequency of the Marx-peaking capacitor loop. This procedure has another advantage - it will also greatly reduce the waveform "notch" as described in Section III of this memorandum. Returning to the prepulse, increasing the Marx inductance by a factor of two and similarly increasing the peaking capacitance by a factor of two by adding four more arms will slow the charging of the peaking capacitors by half and reduce the prepulse by half. Adding more peaking arms will slightly increase the stray capacitance between the pulser assembly and ground, but this effect will hardly be noticeable. In this way, the prepulse can be reduced from 30 to about 15%. The flashover voltage of the switch housing is slightly time dependent, so it is probably not advisable to slow the system down by much more than a factor of two. Reducing the prepulse will also increase the overall voltage applied to the main switch, in this case by about 15%. Since housing flashover has apparently not been a problem in the main switch it is likely that the design is adequate to support 15% more voltage for a longer period of time.

The Marx inductance must be increased in a distributed way. Simply adding lumped inductance somewhere in series with the Marx will not work, since the stress across this inductance will be quite high. The simplest way to increase the overall loop inductance is to increase the spacing between the Marx generator and the peaking capacitor array, as discussed below.

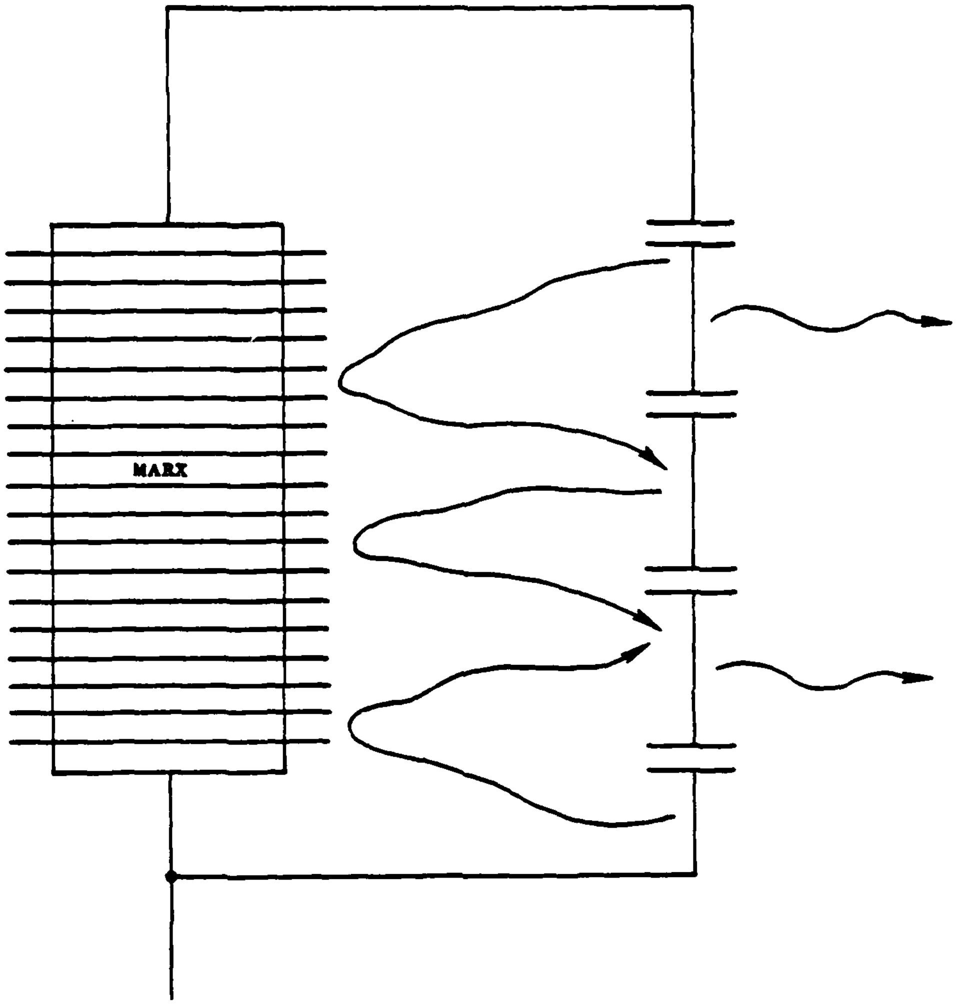
III. ELIMINATION OF PULSER "NOTCH"

There are several ways of thinking about the cause of the "notch" in the TRESTLE pulser output. It arises from the coupling between the Marx generator column and the peaking capacitor array, and Dr. Giri of LuTech has modeled this coupling as a pair of transmission lines and produced the slowed risetime and postrise waveform oscillations similar to the "notch" in his computer analysis. Since the peaking capacitors charge in 90 ns, equivalent to a transit length of 90 ft., and the pulser is closer to 15 ft. long, another convenient way to think about the "notch" is from the lumped circuit viewpoint.

From this viewpoint, the current flowing in the peaking capacitors produces a magnetic field which encircles the peaking capacitor array, much of which passes through the space between the peakers and the Marx on the Marx side of the capacitor assembly. The firing of the main switch sends a current pulse through the peaking capacitors in the direction opposite to the current set up by the Marx generator in these capacitors. As this wave sweeps across the peaking capacitor array, the correct response of the peaking capacitors is to allow a state of zero current to be set up at once. This in effect transfers the current already built up in the Marx generator column to the load in one wave transit of the peaking capacitor array. This "distributed" peaking capacitor idea works very well in pulsers that have cylindrical symmetry such as the HPD or TORUS pulsers. In that case, the magnetic field existing between the Marx column and the peaking capacitors is not affected by the current flowing in the peaking capacitors but is only a function of current flowing in the Marx column itself. This magnetic field is not changed by moving the peaking capacitors to a larger or smaller radius around the Marx.

In the TRESTLE pulser, however, there is no cylindrical symmetry and the loop formed by the Marx peaking capacitors is linked by a magnetic field which is generated both by the Marx current and the peaking capacitor current. When the wave sweeps through the peaking capacitor column, the presence of the low-inductance Marx generator across the peaking capacitor assembly opposes the sudden change of this magnetic field. If the Marx loop had zero inductance, this magnetic field would be effectively locked at a constant value and could not change at all. In that limiting case, the TRESTLE output pulse would consist simply of a spike generated as the energy stored in the stray capacitance between the peaker array and ground is swept out by the main switch firing. Something very like this is happening in TRESTLE, and only one cure is apparent. It is not practical in the TRESTLE case to restore cylindrical symmetry to the pulser by surrounding it with peaking capacitor arms. Consequently, the Marx generator inductance must be increased so it relaxes its grip on the peaking capacitors more quickly. A kind of symmetry could be provided for TRESTLE by installing the Marx in the same plane as the peaking capacitors with a number of peaking capacitor arms on either side of the generator. This, however, would expose the Marx to the wave being launched at the working volume and the Marx itself is too complex a structure to allow this wave to propagate at the same velocity that it propagates in the volume between the peakers and the ground plane. So this procedure would undoubtedly introduce other waveform oscillations into the output.

Another way of thinking about this same effect is sketched in Figure D1. A facility like TRESTLE, which is formed of a sector of a bicone, will radiate initially in all directions. The peaking capacitors will radiate in the direction of the Marx generators as well as in the direction of the working volume. What is happening now is that the Marx generator is blocking this "backwave" radiation and reflecting it back toward the peaking capacitors and working volume. Much of this energy is trapped in the space between the Marx and peakers and the wave launcher cannot behave normally until this energy is dissipated. By moving the Marx away from the peaking capacitor assembly as sketched in Figure D2, more of the backwave will be allowed to escape from the system. It is necessary that this backwave be generated and radiated in order to set up the right boundary conditions outside the array for propagating the wave inside the array. If the external wave is not permitted to run from the pulse source along the outside of the array, then the energy to supply this external field will be extracted from the fields inside the simulator, with a consequent loss of risetime at the working volume of the simulator. Energy will flow around the edges of the transmission line to the outside until the necessary field intensity on the backside of the array is established.



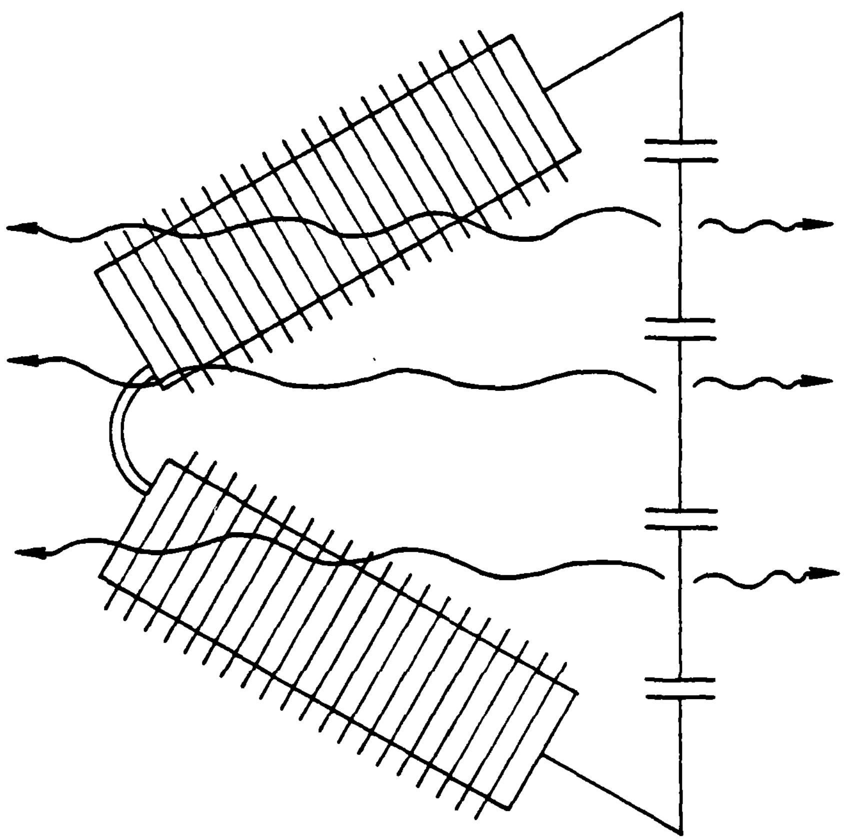
THE PROBLEM:

THE INDUCTANCE OF THE GENERATORS NOW AT TRESTLE IS TOO LOW.

BECAUSE OF THIS, THE GENERATORS TRAP ENERGY FROM THE PEAKING CAPACITOR BACKWAVE.

THE TRAPPED ENERGY INTERFERES WITH THE FORWARD RADIATION WAVE YIELDING A VERY POOR TRESTLE OUTPUT.

Figure D1.



SOLUTION:

THE PEAKING CAPACITOR BACKWAVE IS INEVITABLE, THEREFORE THE MARX MUST BE RECONFIGURED TO LET BACKWAVE PASS.

TO DO THIS THE INDUCTANCE AND RESISTANCE OF THE MARX MUST BE INCREASED.

THIS CHANGE WILL ALSO ELIMINATE THE PRE-PULSE IN THE TRESTLE OUTPUT WHICH IS ENHANCED BY THE EXISTING LOW MARX INDUCTANCE.

Figure D2.

Low-level pulse experiments conducted by driving the main switch with a repetitive pulse generator for example, will fail to identify this problem since the Marx generator switches are open for such experiments. To observe the Marx generator acting as a shield against the backwave, the Marx must be erected. In low-level pulse propagation tests (TDR, RPG) the Marx switches must be individually short-circuited. Since this is excluded under the present ground rules, we recommend no further experiments be done.

In summary, the same action that reduces prepulse also reduces the pulser "notch" and improves the high frequency response; slowing down the peaking capacitor charging time by doubling the number of parallel peaking capacitors and increasing the Marx loop inductance also permits more backwave energy to be launched. This might cost about 10% in peak voltage, since the peakers will be a heavier load on the Marx. However, the Marx-peaker loop resistance should be reduced, so the Q should be enhanced; this will add a little voltage gain to the CLC circuit and help compensate for the heavier load. Also, the main switch should be able to be fired a little past the theoretically ideal quarter-cycle firing time without producing the pronounced notch. This will restore the peak output voltage.

IV. MAIN SWITCHES

The remaining limitation in TRESTLE is pulse shape variation due to side-to-side asynchronism between the two pulsers. In the several years since TRESTLE was designed, high voltage switching has come a long way, and a simple modification of the existing TRESTLE switches can be effected that will remove most of the asynchronism. At present, the asynchronism ranges out to 20 or 30 ns. This much scatter can be removed by using the PBFA-style switching technique now used by Sandia. The switches are converted to a uniform-field design by installing hemispherical electrodes. In the anode side of the switch, a small ultraviolet (surface-flashover) source is installed. This source is pulsed on when the dark switches have just passed through their static breakdown voltage. As is well known, dark gas spark gaps exhibit an "impulse ratio"; the breakdown voltage measured with a fast-rising pulse is considerably higher than with d.c. By turning on a u.v. source after the switch has passed through its d.c. breakdown voltage, but before it reaches its pulsed breakdown level, the switch breakdown can be accelerated. Careful control of the u.v. source timing will produce simultaneous breakdown in both TRESTLE output switches. This can be carried out, as sketched in Figure D3, by adding two fiber-optic isolated trigger sets identical to the ones now used to fire the TRESTLE Marx generators. These sets have a demonstrated rms jitter of less than 2 ns over 100-shot groups.

Side benefits of this improvement in the output switches will be a slightly faster switch risetime, since the gap stress can be increased with a uniform-field geometry over that of an enhanced-field system. Also, any "sizzle" current now present and contributing to the prepulse will be eliminated.

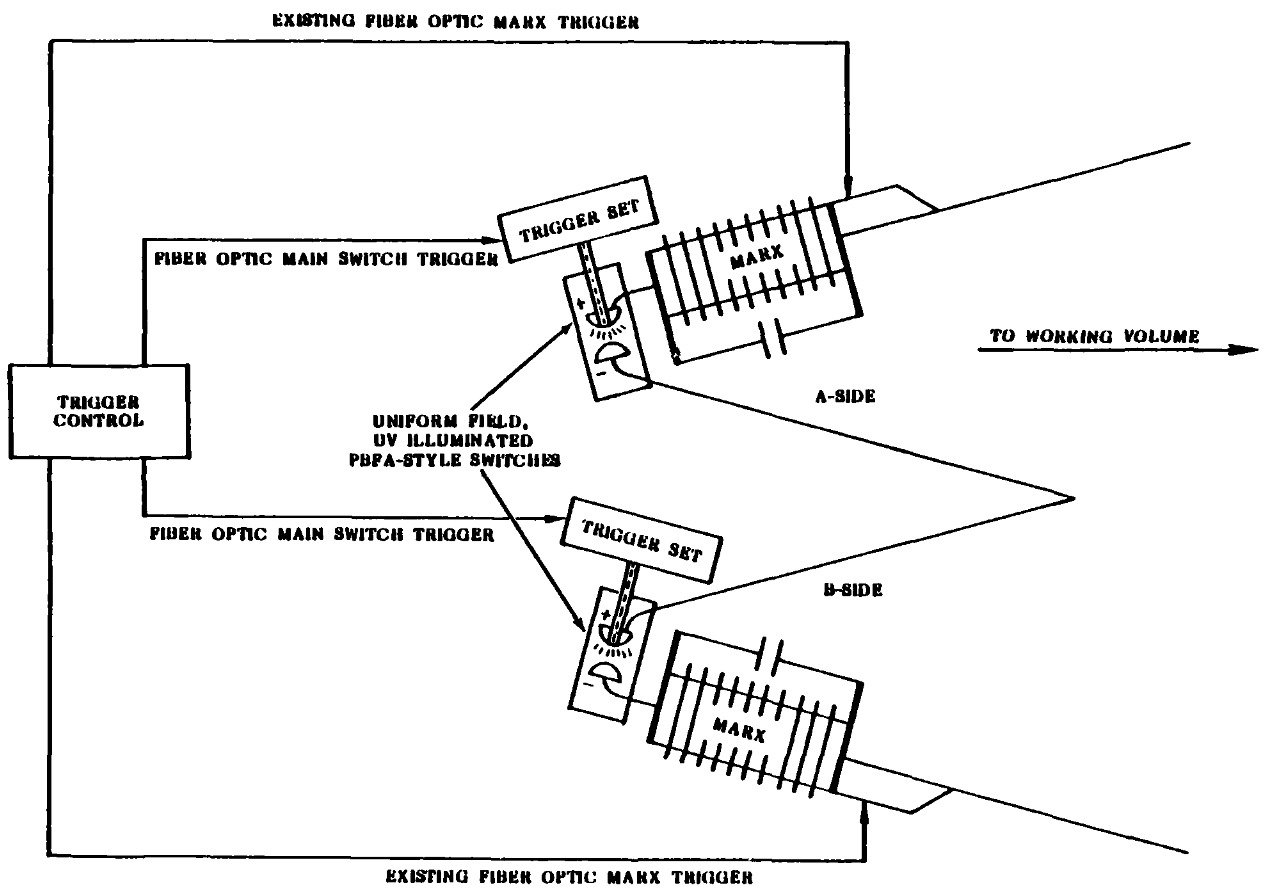


Figure D3. Synchronized output switches for TRESTLE.

V. SUMMARY

In summary, Pulsar recommends that the TRESTLE pulsers be modified now to include eight peaking arms, an increased spacing between Marx and peaking array (possibly requiring an addition to the gas enclosures) and an ultraviolet-triggered output switch system of the PBFA type. These changes will reduce the prepulse by about half, will reduce the pulser "notch" considerably, and will remove most of the waveform variation in the working volume now caused by residual pulser asynchronism. A faster working volume risetime will also result, since the pulsers will be more free to establish the required "backwave" fields on the simulator array, and the main switches will close more rapidly. It is interesting that MLI noted in one of the TRETM memoranda that doubling the peaking capacitance seemed to remove the waveform notch. Because no reason for this improvement could be adduced at the time, the idea was apparently abandoned. It is time to resurrect it.

APPENDIX E

TRESTLE TEST PLAN
AND
PRELIMINARY ASSESSMENT

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Oakland, California

I. INTRODUCTION

This report contains a suggested plan devised by Pulse Sciences, Inc. for a program of tests that would determine how best to modify the pulse generators of the AFWL TRESTLE EMP Simulator in order to improve the output waveform.

The test plan was developed with several aims in mind. One was that it should be reasonably thorough and be able in a logical way to address all of the deficiencies that have been identified as potentially significant. Another aim was to be flexible and let the course of the tests be influenced by results as they are obtained. A third aim was to recognize that the preliminary assessment made so far already suggests which of the deficiencies are the most important and what degree of correction is possible.

The preliminary assessment is summarized in Section II, Part 1 and the improvements possible are estimated in Section II, Part 2. The test plan and rationales are described in Section III.

II. PRELIMINARY ASSESSMENT

1. QUALITATIVE SUMMARY

a. The waveform notch, together with late time distortion from the desired exponential waveform, is almost certainly due mainly to the peaking capacitance value being too small. This can be corrected by adding more peaking capacitors of the same type in parallel. Other possible contributions to the notch (or at least to waveform perturbations near peak), but probably not the later time distortion, are as follows.

1. Propagation of a wave on the transmission line formed by the Marx generator and the ground plane. This could be alleviated by adding more peaking capacitors to better screen the Marx from ground, by changing the position of the Marx, or possibly by increasing the Marx inductance.

2. Reflections between the output switch and the transition region of the output conductor. These can be smoothed out by attaching extra peaking arms to the upper and lower edges of the transition.

3. Loop currents circulating between peaker arms. These can be eliminated by cross-connecting the peaker arms at points along their length, to make smaller loops.

4. Resonances inside the peaking capacitors; these would require the peaking capacitors to be redesigned.

b. The long risetime in the test volume is due in part to the risetime of the pulser and in part to deficiencies in the remainder of the simulator; namely the wood forming the platform and support, and the wave propagating properties of the transmission line array. The main cause of the pulser risetime is probably the internal reactance and high external wave impedance of the peaking capacitor arms. This can be partly corrected by the use of more peaker arms of the same type in parallel; the same identical capacitors could probably be used since an increase of capacitance is in any case called for to reduce the notch. It is doubtful whether any further improvement than this to the pulser risetime would give a significant improvement of risetime in the test volume. However, further improvement might be made by redesign of the peaking capacitors (both internal design changes and shortening), and by addressing other possible contributions to risetime, which are as follows.

1. The output switch; the configuration might be changed to match the fields on the wave launching structure better, or the spark channel might be shortened, or more channels created.

2. Partial reflection of the leading edge of the pulse from the transition region.

3. Propagation of a slow wave on the Marx.

Items 2 and 3 can be corrected as discussed earlier when dealing with the notch.

c. The large prepulse is probably due entirely to the capacitance to ground of the output switch high voltage electrode and the peaking capacitors. Increasing the peaking capacitance, as is required to eliminate the notch, will slow the peaking circuit and reduce the prepulse. Further slowing of the circuit and reduction of prepulse is possible by increasing both the peaking capacitance and the Marx inductance together. Redesign of the peaking capacitors to shorten them would result in some further prepulse reduction, but would require the Marx to be moved away from the peakers and the gas house to be enlarged.

Thus all three defects in the output waveform, the notch, the slow rise and the large prepulse, are expected to be alleviated, and in the case of the notch almost eliminated, by adding more peaking arms of the same type in parallel with the present peaking arms. A concern, however, is that the resultant slowing of the peaking circuit, by increasing the charge time of the output switch, will increase switch jitter; and it may also lead to breakdowns between Marx and the peakers, or from the Marx, the peaker, or the switch high voltage electrode to ground. Further slowing of the peaking circuit beyond that required to eliminate the notch, in order to eliminate prepulse, increases these possibilities, which must be checked.

2. ESTIMATED IMPROVEMENTS

The following are very preliminary estimates of the improvements in risetime, notch and prepulse that might be obtained by modifying the TRESTLE pulser.

a. Risetime--The risetime measured near the apex of the TRESTLE wedge is 22.0 ns averaged between the two sides (ATLAS Memo 28, Table 2-1). At the front of the platform (Test Point 1) the risetimes are 26.5 ns for H and 31.3 ns for E, and at the center of the platform (Test Point 2) these become 37.5 ns and 38.8 ns.

The differences between the risetimes of E and H may be due to the presence of the wood, though it is not clear on this basis why the difference at the front of the platform should be in the sense observed. For the present purposes we shall use the averages of the risetimes of E and H, namely 28.9 ns at the front of the platform and 38.1 ns at the center.

To estimate the maximum improvement that might be obtained by improving the pulsers suppose that the 22.0 ns risetime near the wedge apex is entirely due to the pulsers. Next, make a fairly optimistic assumption that this might be reduced to 11 ns. This corresponds to line 5 of Table D11 in the report on the "Low Voltage Spring Tests", taking the most realistic estimate of pulser risetime to be that given by the PI probe just outside the transition region. The test configuration for line 5 has the 88 Ω monocone output switch, mounted vertical, and the peaking capacitors replaced by metal tubes.

The manner in which the risetime at the wedge apex adds to the degradation between the apex and a point at or near the platform depends on the exact forms of both the risetime and degradation. We can assume for example linear addition of risetimes or addition in quadrature. Assuming that the pulses risetime decreases from 22 ns to 11 ns, we then obtain the results shown in Table E1. The truth probably lies in between linear and quadrature addition so that we may estimate roughly 20 ns at the platform edge and 30 ns at the center.

TABLE E1

Platform Risetimes Predicted For An 11 ns Pulser Risetime

Location On Platform	Present Risetime	Predicted Risetime: Linear Addition	Quadratic Addition
Front Edge	28.9	17.9	21.7
Center	38.1	27.1	33.0

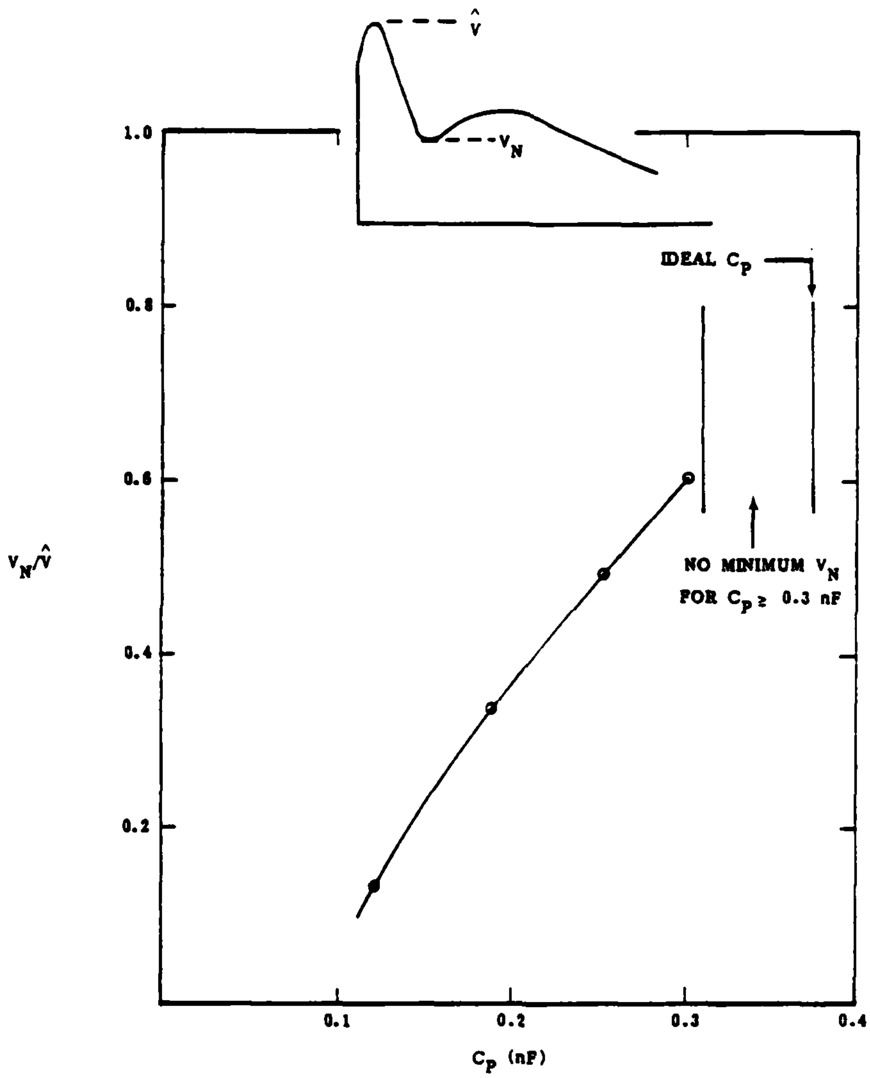
Because the assumptions are optimistic, the actual improvements practical on the platform are probably somewhat less. However, it must be reiterated that they are quite uncertain.

b. Notch--For a Marx capacitance of 3.17 nF and inductance of 9.4 μH as given by MLI, the peaking capacitance ideal for driving 150 Ω is 0.37 nF. The output switch should be closed at about 94 ns.

Calculations were made to see the depth of the notch as the peaking capacitance is reduced. These are shown in Figure E1. The switch closure time remaining 94 ns. An output switch inductance of 0.94 μH is assumed.

Determination of the actual depth of the notch is made difficult by the presence of prepulse, which must be subtracted from the waveform; however, the notch may be estimated to reach a minimum of somewhat less than 50 percent of peak when the switch closes at the normal time. This suggests that the peaking capacitance is about 0.25 nF.

On this basis, the notch could be removed by adding two more peaker arms like the present arms. Other sources of waveform distortion would remain, but the results of TRETM 13 suggest that these would represent effects of order 10% or less.



(3.17 nF, 9.4 μH MARX, 150 Ω LOAD, 0.94 μH SWITCH, NO PREPULSE,
94 ns SWITCH CLOSURE AS FOR IDEAL 0.37 nF C_p)

Figure E1. Minimum notch voltage vs. peaking capacitance.

c. Prepulse--The prepulse as a fraction of Marx voltage (which is equal to the output voltage in a correctly designed peaking circuit) is roughly

$$\frac{Z\ C_s\,C_o^{\ 1/2}}{(C_o + C_p)^{1/2}\ C_p^{\ 1/2}\ L^{1/2}}$$

where Z is the load impedance, L the Marx inductance and C_o, C_p, C_s are the capacitances of the Marx, the peaker and the switch.

Assuming that C_s = 0.12 nF and that C_p = 0.25 nF at present, this is about 35% (about 30% is observed). If C_p is increased to the correct value of 0.37 nF, prepulse reduces by about one sixth - to 29% in the calculation.

If a further factor two reduction of prepulse (to a theoretical 15%, say) was attempted by further slowing the peaking circuit, the Marx inductance would have to be increased to about 18.5 μH and the peaking capacitance to 0.65 nF - perhaps 10 of the present arms. The time to switch closure would increase from 94 ns to about 178 ns. The presence of the large number of peaking arms might be useful in reducing the risetime, but the long charge time would almost certainly require the switches to be triggered.

It is estimated that about 40% of the 0.12 nF stray capacitance is due to the peaking capacitors, so that even if the peaking capacitor length were halved, the prepulse would only decrease by about one-fifth.

III. TEST PLAN

1. TEST PLAN SUMMARY

The test plan recognizes that the largest uncertainties at the outset are how to improve the pulser risetime, what improvement can be obtained, and how much this improvement will be reflected in the test volume. The means of improving the notch and prepulse, and the improvements that might be obtained in each case, are much better understood.

The test plan, which is diagramed in Figure F2, therefore begins (Task 1: Risetime Analysis) by obtaining data from the existing TRESTLE system and analyzing these to determine approximately the contribution of the pulser to the test volume risetime. If the pulser contribution is substantial, so that its reduction appears desirable, the plan proceeds to identify how this reduction would be made through Task 2: Pulser Injection Tests. Here a specially constructed fast-risetime low-voltage pulse generator drives the TRESTLE simulator through one pulser. Tests are made to determine which features of the TRESTLE pulser are responsible for the risetime and how they may be improved. Some information may also be obtained about the notch.

If, however, the results of Task 1 indicate that any plausible improvement of pulser risetime will not have a substantial effect in the test volume, Task 2 is bypassed. In case the results of Task 1 are unclear, the first part of Task 2 is designed to provide a more accurate assessment of the risetime improvement available in the test volume, by making a test with a nearly-ideal pulser configuration; following this (subtask 2a), the larger part of Task 2 can again be bypassed if the results so indicate.

In Task 3, the number and configuration of the peaking capacitor arms in one TRESTLE pulser are varied. The objective is to eliminate the notch. Some reduction in risetime and prepulse is also expected.

FIGURE E? TEST PLAN FOR TRESTLE UPGRADE

TASK 1: RISETIME ASSESSMENT

Uses existing system; obtains and analyses data

Might risetime on platform be significantly reduced by improving pulser?

YES ⇓ NO ⇒ (to Task 3)

TASK 2: PULSE INJECTION TESTS

One Trestle pulser is modified to accept an external pulse generator

2a: Establish best attainable risetime and pulse-shape

Is significant risetime improvement on platform confirmed?

YES ⇓ NO ⇒ (to Task 3)

2b: Identify sources of pulser risetime; establish corrections.

TASK 3: PEAKING CAPACITOR OPTIMIZATION

Uses on Trestle Pulser at Reduced Voltage

Test different numbers and combinations of peaker arms to minimize notch, improve risetime and prepulse.

TASK 4: SWITCH INVESTIGATION/PREPULSE ASSESSMENT

Uses one Trestle pulser with added peaking capacitance at full voltage.

4a: Test with normal switch out time.

Should prepulse be further reduced?

YES ⇓ NO ⇒ (to Task 5)

4b: Test with delayed switchout.

TASK 5: UPGRADE ASSESSMENT

Paper study.

Can adequate upgrade be made by combining identified modifications, using existing components?

YES ⇓	NO ⇓
FINAL UPGRADE DESIGN	Further Development Outside Trestle. e.g.

Triggered Output Switch	Improved Peaking Capacitors	Relocate Marx	Increase Marx Inductance

Task 4 is a characterization of the output switch. Changes made to the peaking capacitors may have increased switch jitter, and a test is first made (4a) to determine if the jitter is still low enough, or if an improved switch must be developed in order to implement the improvements identified so far.

The results of the first switch tests and an assessment of the prepulse reduction made so far are then used to determine if further prepulse reduction is desirable and feasible. If so, further tests on the switch are carried out (4b) to show how far the prepulse reduction might be carried.

Task 5 is a paper study that integrates the conclusions of the various tests to formulate the best upgrade possible, first using only existing components and second assuming additional development. Necessary or desirable development programs are specified.

The main choice to be made in the test plan is how much effort to spend on understanding and improving risetime, i.e., whether to perform Task 2. As presented above, this choice would be made after reviewing the results of Task 1. An alternative and slightly different approach is to plan from the outset to omit Task 2 and proceed from Task 1 to Task 3. Task 3 is expected to yield some improvement in risetime, and this can be assessed in the light of Task 1 results. A decision to perform Task 2 after all can still be made, if warranted, after Task 3. The external pulser and other equipment needed for Task 2 can then be built while Task 4 is being performed. In this scenario, Task 1 is still performed.

2. DETAILED TEST PLAN

a. Task 1: Assess possible risetime improvement--This task is accomplished without modification to the pulsers. The objective is to identify the pulser risetime and see how it changes, first on its way to the test volume and then as the pulse passes through the wooden structure. The risetime and pulse shape are measured at the following places.

(1) Just beyond the pulser transition.

(2) Part way along the wedge (about 60 feet).

(3) Near the apex of the wedge.

(4) In front of and clear of the platform.

(5) At one or two important points on the platform.

Measurements (1) and (2) identify the pulser risetime. Measurements (2), (3) and (4) show if the risetime is increasing as the pulse passes through the transmission line array. Measurement (4) must be made in the plane of symmetry, with at least 30 ns clear time from the main wooden structure. Measurement (5), which is also made in the plane of symmetry, shows the effect of the wood and should include at least the horizontal E-field and vertical H-field.

From these measurements it will be possible to assess to what extent the risetime in the test volume is due to the pulser and to what extent to the array and the wood, and hence to deduce what improvement is possible in the test volume as a function of improvements made in pulser risetime. Given accurate measurements of the waveform at the pulser and in the test volume, a numerical "deconvolution" can be performed to determine the test volume waveform produced by a pulser waveform that is a step function with a risetime somewhat greater than the resolution of the measurements. From this "transfer function" in turn, the test volume waveform can be calculated for any other pulser waveform with greater risetime. Similar calculations are of interest for the point in front of the platform if it is anticipated that the wood might be improved from its present condition or that tests could be performed in this region.

In order to check the accuracy of the "deconvolution" calculation, it is desirable to take two sets of data with different output switch closure times. These will have different waveshapes, but the transfer function will not be affected if correctly calculated.

Strictly speaking, the only measurements required for the task objectives are those at the pulser and at or near the test volume (locations (1), (4), and (5)). However, measurements at location (2) are desirable to confirm the pulser risetime, because measurements near the transition may be affected by non-TEM modes propagating a short distance from the pulser. Measurements at location (3) should help understand the origin of any contribution to the risetime from the transmission line arrays. This understanding would be aided by data taken with only one pulser, which would help identify reflection and diffraction effects.

It is possible to make simultaneous measurements of the fields near the ground plane opposite the pulser in order to attempt to understand what is happening to the risetime at various points within the pulser, even though this is not the objective of this task. However, these measurements will be very difficult to interpret because of the different propagation directions and modes that will be present in the region. It is likely that the only data of this kind worth taking is the E-field and H-field (voltage and current, in effect) at the output switch; this can help determine whether the switch or pulser affects the risetime most.

In this task, data should be obtained both at full voltage (the maximum operating voltage), and also at a lower voltage, anticipating the later tasks will use a lower voltage to facilitate experimental modifications of the pulser. The voltage chosen should be the lowest one at which the pulser operation is still representative of its normal use.

It is possible that the result of this task would be a decision that no effort at reducing the pulser risetime is worthwhile. In that case, work would proceed to Task 3.

b. <u>Task 2</u>

(1) <u>Subtask 2a: Pulse injection tests</u>--Verify the attainable risetime and pulse shape. The objective here is to verify that the improvement in test-volume risetime deduced to be possible from the measurements of Task 1 can indeed be obtained, and with a pulser whose general configuration is like that of the existing TRESTLE pulsers; and to establish a baseline for assessing the deficiencies of the pulser.

For this, the pulsers are modified to allow an external pulse to be injected at the apex of a near-ideal extension of the 150 Ω transmission line. A tapered metal plate (possibly of mesh) is placed on the ground side of the peakers, extending the ground-side surface of the transition region back to the line apex,

Figure E3. (The output switch is removed to allow this extension) back to the line apex, Figure E1. In addition, metal wires or tubes are introduced that connect from the apex to the upper and lower ends of the transition region, so that the transition region is driven with current in a relatively smooth manner and no longer represents a perturbation to the wave.

The external pulser used to drive the line apex should have a risetime of no more than a few nanoseconds, which implies a pulser inductance of no more than about 200 nH. This inductance is readily achievable at about 100 kV. The amplitude should be sufficient to obtain one or two nanosecond resolution and accuracy for field measurements in the test volume. For the purposes of this task, since the transmission line presents a well defined 500 Ω impedance to the external pulser, the pulser could be capacitive with a decay time about equal to that of the TRESTLE pulser (i.e. be a 3.2 nF capacitor) or could be resistive (e.g. a 50 Ω cable pulser). However, for subsequent use in Task 3, a 10-20 nF capacitive pulser is desirable, to present a low impedance to reflections from the TRESTLE pulser. This will produce a decay time of 1.5 to 3 μs. The other TRESTLE pulser should be shorted to allow complete discharge of the capacitor.

The principal measurements to be made are the risetimes and pulse shapes in the test volume and in front of the platform (locations (4) and (5) in Task 1). Measurements at location (2), just outside the transition, will serve to show if this is still producing a noticable degradation.

The result of the measurements in this subtask is a verification and more accurate measurement of the transfer function between a nearly ideal pulser and the test volume.

This could again lead to a decision not to pursue risetime improvements further but to proceed instead to Task 3: Peaking capacitor optimization. Otherwise the results will serve as a baseline for subtask 2b.

(2) Subtask 2b: Identify sources of pulser risetime--In this subtask, the pulser deficiencies that are suspected of contributing to the risetime are added one at a time to the near-ideal configuration set up in subtask 2a. The external

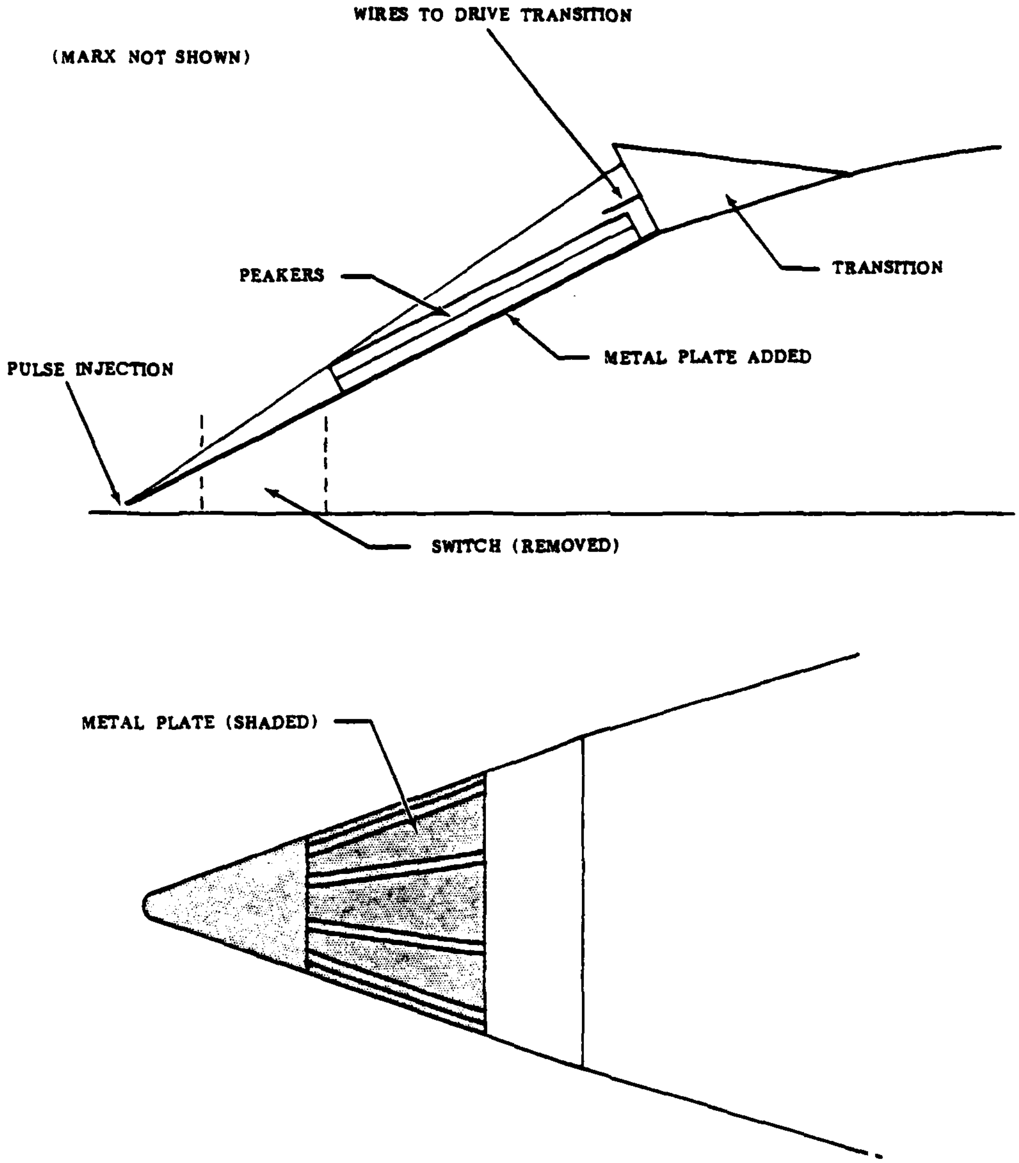


Figure E3. Modification of TRESTLE pulser to accept external pulse.

pulse injector is again employed. The effect of each deficiency on the risetime and pulse shape is measured part way (about 60 feet) along the wedge. Measurements in the test volume are of interest, but may be hard to interpret, while measurements just outside the pulser transition may be affected by non-TEM modes propagating short distances from the pulser.

The effect of each deficiency can thus be isolated to determine which produces "significant" degradation of the risetime, and to find how to alleviate the effect. Prior to the task, the level of degradation considered significant is determined with the help of the results of Task 1 and subtask 2a.

After each deficiency is added and evaluated, it is removed again unless its effect is found to be very small.

Below is a list of the identified deficiencies and the further tests to be done if each is found to be significant.

(a) Output switch--This (or a dummy high voltage conductor) is placed back in the circuit; the metal plate on the ground side of the peaking capacitors is left in place beyond the switch. The switch high voltage conductor is driven by the external pulser at its tip, where the spark closes in normal operation.

If degradation is found to be significant, other dummy high voltage conductors with different shape are substituted to see if improvement can be obtained. Each shape must be judged capable of incorporation in a practical 5MV switch.

(b) Output transition--The wires driving the edges of the transition are removed. If the effect is significant no further test of this is needed.

(c) Peaking capacitors - external configuration--The metal plate on the ground side of the peaking capacitors is removed and the capacitor arms are individually wrapped with continuous metal foil.

If degradation is significant, metal cylinders representing more peaking arms are added between the present arms, to determine how many are needed to make the degradation insignificant. This should be guided by prior theoretical studies of the wave impedance of the region for different numbers of capacitor arms.

(d) Peaking capacitors - internal configuration--The foil wrap around the peaking capacitors, and the wires driving the output transition, are removed. The external pulser now drives the array through the capacitance of the peaking arms; previously these have been shorted by the foil or by the metal plate on the ground side. Thus in this test, the decay time of the output waveform in the transmission line will be 150 C_p (ns) (where C_p is the capacitance of the peaking capacitors) or about 50 ns, rather than the 1.5 - 3 μs decay of the external pulser.

An accurate effective value of C_p can be determined by measuring this decay time.

To allow the pulser and peaking capacitances to discharge, a resistance in the 10 kΩ to 100 kΩ range must be placed across one of the peaker arms.

If degradation is significant, additional peaker arms must be added. The first arms should be added in the location of the wires that drove the transition region. If the improvement obtained by adding arms is inadequate, the effect of shortening the arms can be checked by shorting individual capacitors with foil wrap.

(e) Net risetime measurement and Marx check--To complete this subtask, the corrections found for the significant deficiencies should be added simultaneously and a test made to determine the net improvement. Then, one or two insulated conductors must be wound around the Marx in loose helices, to represent the conduction path that normally exists. If this leads to a significant degradation in risetime or pulse shape, the inductor representing the Marx must be moved to other locations in which the Marx might be placed; such as farther from the peaking capacitors, or rotated into a different direction.

These Marx locations may extend beyond the gas box, necessitating temporary connections through the wall.

(c) Task 3: Peaking capacitor optimization--This task is performed using one of the TRESTLE pulsers. The operating voltage should be the lowest at which the pulser operates in a representative fashion, to facilitate modification without risk of breakdown. Preferably, the pulser should operate in air, in order to save time filling and recovering SF_6 between modifications.

The main activity in this task is to add peaking capacitor arms in parallel with the existing arms and determine what peaking capacitance gives the best waveform. The additional arms are assumed either to be spares or to be obtained from the second pulser. The second pulser is shorted to ground at the transition.

(1) Subtask 3a: Check of Marx inductance and peaking capacitance--The pulser is allowed to ring without closure of the output switch, first with the normal peaker configuration and than with all peaker arms wrapped with foil. The frequency of ringing in the second case determines the inductance of the Marx - peaker loop. From this and the frequency in the first case, the sum of the effective peaking capacitance and the effective stray capacitance can be obtained. It is assumed that the Marx capacitance is accurately known.

(2) Subtask 3b: Addition of extra peaking arms--The location in which the extra arms are added should be guided by previous theoretical studies of how to make the effective wave impedance 150 Ω and of how to equalize the currents in the arms. However, assuming that previous tests in Task 2 have shown the desirability of driving the edges of the transition section, the first step is to add two peaking capacitor arms out in this region. Because these arms will be outboard of the present four arms and somewhat farther from ground, they will result in a more equal current distribution. After this, arms can be added in the plane of the first four; for example, first, one in the center, then two in symmetrical positions instead, then all three together. The choice of location should take into account the effects on risetime found in Task 2.

For each peaking capacitor configuration, the output switch firing time must be varied to obtain the best output waveform. The waveform should be measured 60 feet along the wedge, since this gives ample transit time isolation from the wedge apex (over 400 ns).

The addition of capacitor arms can be halted when a good exponential decay is obtained with no notch, or when no further improvement is possible. If all available peaking capacitors are used before this point is reached, peaking capacitance can be increased by shorting out peaking capacitor sections with foil wrapped around them.

If undesirable perturbations still exist on the waveforms after this part of Task 3 has been carried out, then subtask 3c should follow.

(3) Subtask 3c: Cross connection of peaker arms--To reduce circulating currents, cross connections are made between all peaker arms at two or three roughly equidistant junctions between capacitors. More junctions are cross-connected if this is warranted.

(d) Task 4: Switch investigation and prepulse assessment

(1) Subtask 4a: Switch investigation--Task 3 determines the peaking capacitance needed to eliminate the notch and produce an optimum waveform with nearly exponential decay. Assuming that the addition of substantial peaking capacitance has been found necessary, the charge time of the output switch will have increased. Task 4 first checks that this does not result in breakdown or excessive output switch jitter.

First the peaking capacitor configuration with optimum capacitance (or as near optimum as possible) must be modified to allow full voltage operation, eliminating any temporary supports or connections used at lower test voltages. Then the voltage must be raised in steps to full voltage, with the output switch closing at optimum time. Jitter is measured at each step. The increase in switch gap length needed to reach full voltage is also of interest, since it will affect the risetime.

(2) Subtask 4b: Assessment of feasible prepulse reduction--Some reduction of prepulse will have been achieved by adding the extra peaking capacitance needed to eliminate the notch, because of the effect of this in slowing the peaking circuit. Further reduction of prepulse will require the peaking to be slowed further by adding peaking capacitance and circuit inductance simultaneously, in a prescribed way.

The decision on whether to attempt further prepulse reduction should take into account several factors:

(a) The degree of reduction already achieved, which depends on how much extra peaking capacitance was needed to eliminate the notch;

(b) The results of the switch investigation in part (a) of this task; if these results indicate that switch jitter is just acceptable with the increase of charge time needed to eliminate the notch but is increasing markedly with charge time, then further reduction of prepulse will require the development of a triggered output switch;

(c) The increase of circuit inductance is not readily obtained - it will necessitate modifying the Marxes, probably in every stage.

If it is decided to pursue further prepulse reduction, the still longer charge time may be simulated by increasing the output switch pressure or spacing, and lowering the Marx charge so that the switch breaks down at the same voltage but progressively later in the waveform. Jitter and switch gap length are thus obtained as a function of charge time and dV/dt, and the ability to hold voltage for longer times is verified, albeit with a charging waveform somewhat different from the normal case.

From the data so obtained it will be possible to assess the effect on the switch of suppressing the prepulse to various further degrees.

Because of polarity effects in SF_6, it is necessary to carry out this task for both pulse polarities. This can be done either by modifying and testing both TRESTLE pulsers in turn, or by reversing the charge polarity on the pulser initially modified and substituting the output switch with that from the other polarity pulser.

(e) Task 5: Upgrade assessment--This is not an experimental task, but one that uses the results of Tasks 1-4 to formulate the over-all upgrades that are possible.

(1) Subtask 5a: Upgrade based on present components--The improvements that Tasks 1-4 show to be possible using the existing Marx, peaking capacitors (in larger numbers), and output switch are combined in a consistent way. For example, the optimum number and placement of peaking arms is determined taking into account the effects on notch, risetime, prepulse and switch jitter.

The mechanical design changes needed to effect such an upgrade are identified and formulated.

(2) Subtask 5b: Upgrades requiring further development--These are identified and preliminary plans formulated. Possible developments that may be called for are outlined below.

(a) Low jitter output switch--If the peaking circuit is slowed substantially to reduce the notch or the prepulse, the jitter may become excessive. It will then be necessary to upgrade the switch, probably by introducing an external trigger. Both switch polarities must be considered along with possible trigger isolation requirements. Initially, the state-of-the-art of candidate triggering schemes must be surveyed. These include KrF lasers, V/N electrodes, trigatron electrodes, and electron beam, X-ray and optical triggering. The one that is best for TRESTLE must be selected and a development or test program planned.

(b) Faster risetime output switch--A configuration identified in subtask 2b (a) must be designed into a 5MV version and tested. The advantages of multiple channels that might be obtained by external triggering should be considered.

(c) Increase of Marx inductance and peaking capacitance--Any increase of inductance needed to reduce prepulse must probably be distributed uniformly throughout the Marx stages in order to avoid breakdown. The increase should first be designed into a few stage Marx and the inductance checked or iterated to give the correct value. All stages of both Marxes must then be so modified and the full Marx must be tested. The peaking circuit including the further additional peaking capacitance must then be tested in the TRESTLE pulsers and tuned if need be by making small changes in inductance or in the number of arms.

(d) Relocation of the Marx--Any relocation found necessary to modify the interaction between the Marx and the peakers or ground will almost certainly entail changes to the gas box. The changes must be designed, and probably implemented on one pulser as a preliminary test.

(e) Improved peaking capacitor--If the internal reactance of the existing peaking capacitors is determined to be excessive, an alternative design must be selected or developed. A transmission line test fixture should be devised to allow the properties of specimen improved capacitors to be compared with the existing capacitors.

A higher gradient capacitor may be desirable in order to decrease reactance. This could be incorporated in the existing pulser by spacing new, shorter capacitor sections with conducting elements, provided the conducting elements used are kept short to minimize non-uniformities and enhancements of electric field. Such a design would need to be checked by field-calculations and perhaps high voltage tests.

If the overall length of the peaker array must be reduced, to reduce reactance or prepulse, this will necessitate either folding the two Marxes or moving them away from the peakers, and modifying the gas house.

APPENDIX F

TRESTLE PULSER IMPROVEMENT STUDIES

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San Diego, CA 92123

I. INTRODUCTION AND BACKGROUND

The present TRESTLE system generates an electromagnetic wave spectrum that is deficient in moderate to high frequencies. This is the result of two phenomena, an oscillation or "notch" in the waveform and a degraded risetime. The causes of these problems have been under investigation theoretically for several years now by various investigators, but without the aid of experiments to guide the analysis. At this stage, some key experiments could be done to identify the dominant effects so that near and far term improvements could be considered.

When the problem with the EM spectrum was first identified, an extensive effort to model the pulser was undertaken by BDM under contract to McDonnell Douglas (MDCG 5797). This modeling consisted of calculating, as accurately as possible, the elements of a large equivalent circuit. Values of key elements were also varied to study the influence on the waveform and to achieve the best fit to the data.

The BDM model was able to reproduce the pulse shape within 10%. The basic conclusion was that risetime was influenced strongly by the output switch conic section and the Marx and peaker inductances and that the notch in the waveform was due to the peaker's capacitance being effectively 60% of the stated value. This latter conclusion would have the effect of not allowing the match of the pulser to the load. Tests at Maxwell on the peakers at low (10^3 Hz) and high (10^7 Hz) frequencies are in disagreement with this conclusion, so as of now, this issue is not resolved.

II. PEAKING CIRCUIT MODEL

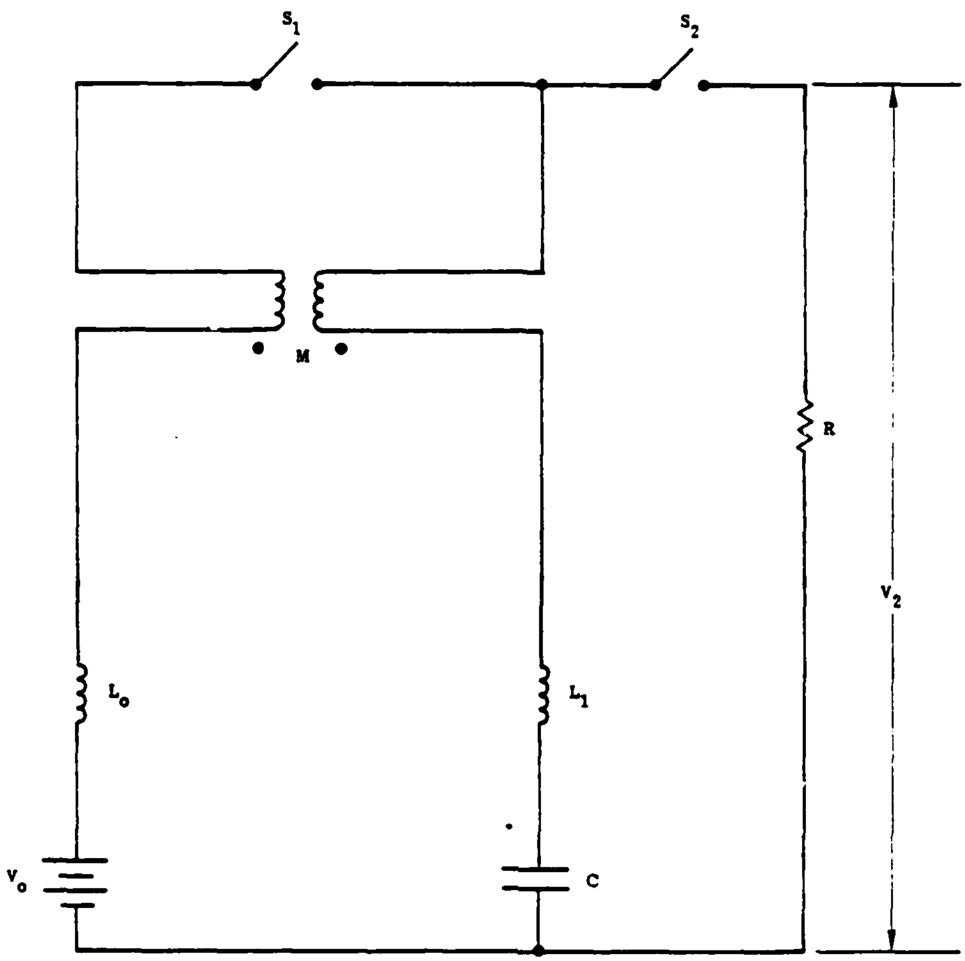
1. GENERAL

In this section we present a circuit model which identifies the major effects on the spectrum of the various parameters in the pulser. The major difference, from a circuit point of view, between TRESTLE and other distributed peaking capacitor circuits is that the Marx charging loop is coupled inductively to the output loop. In other distributed peaking capacitor systems such as TORUS and HPD, the peaker arms were symmetric and there was no fringing magnetic field in the output loop.

In modeling the peaking capacitor arms, the question of how to handle the three inductances associated with the arms, i.e., the internal, external and mutual inductances, must be faced. This problem can be resolved by understanding the operation of the peaking section. Basically, the peaking section is there to allow the Marx current to build up to the desired value before the load is switched in. Afterwards, the peaking capacitor current is zero. In the distributed peaking system, the peaker current is zeroed by the wave launched by the switch closure traveling through the structure. The transmission line that predominantly determines this current is formed by the peaker external inductance and capacitance to ground. Therefore, the external inductance is "invisible" to the peaker operation since in a sense it is balanced by a distributed capacitance. However, the mutual inductance and internal inductance are not balanced by the current distributed capacitance so they can adversely effect the performance.

2. CIRCUIT MODEL

We propose a circuit model of the TRESTLE pulser in Figure F1. Although this circuit may seem somewhat idealized, it contains all the elements of peaking circuit operations with the exception of the prepulse. To simplify the analysis, the Marx generator is taken as a battery. Using this simple model, the sensitivity of the output to the various parameters can be determined by deviation from the ideal response (step function).



V_o = MARX VOLTAGE
V_2 = OUTPUT VOLTAGE
L_o = MARX/PEAKER LOOP INDUCTANCE
L_1 = PEAKER INTERNAL INDUCTANCE
M = MARX LOOP/OUTPUT LOOP MUTUAL INDUCTANCE
C = PEAKING CAPACITANCE
R = LOAD RESISTANCE

Figure F1. TRESTLE circuit model.

This problem is easier to deal with in the frequency domain. The output voltage, normalized to the charge voltage, is given by

$$\frac{V_2}{V_o} = \frac{1 - \omega^2 LC + (L_o - M)\, C\omega^2 \cos\phi + j\,(L_o - M)\,\omega\sqrt{\frac{C}{L}}\,\sin\phi}{j\omega\left[1 - \omega^2 LC + j\left\{\omega\frac{L_o}{R} - \frac{(L_o L_1 - M^2)\,C}{R}\,\omega^3\right\}\right]},$$

where

ω = $2\pi f$ = angular frequency

L = total Marx loop inductance = $L_o + L_1 - 2M$

L_o = self inductance of the Marx loop

L_1 = peaker internal inductance

M = Marx/output mutual inductance

C = peaking capacitance

R = load resistance

ϕ = switching angle.

A more illuminating quantity is the transfer function $j\omega \frac{V_2}{V_o}$

The magnitude is given by

$$T = \left| j\omega \frac{V_2}{V_o} \right|$$

$$= \left[\frac{\left\{1 - \omega^2 LC + (L_o - M)\, C\omega^2 \cos\phi\right\}^2 + \left\{(L_o - M)\,\omega\sqrt{\frac{C}{L}}\,\sin\phi\right\}^2}{\left\{1 - \omega^2 LC\right\}^2 + \left\{\omega\frac{L_o}{R} - \frac{(L_o L_1 - M^2)\,C}{R}\,\omega^3\right\}^2}\right]^{1/2}$$

An example of this function is shown in Figure F2 for parameters approximating those in TRESTLE.

If T is examined in the limit of low and high frequencies, we find that

$$T \to 1 \text{ as } \omega \to o$$

$$T \to \left| \frac{L - (L_o - M)\cos\phi}{L_o L_1 - M^2} \right| R \frac{1}{\omega}$$

This defines a high frequency cutoff f_H

$$f_H = \frac{1}{2\pi} \left| \frac{L - (L_o - M)\cos\phi}{L_o L_1 - M^2} \right| R$$

From this it is seen that the dominant effect on the high frequency response is the peaker internal inductance L_1. For example, if $L_o = 12.7\ \mu H$, $M = 2\ \mu H$, $L_1 = 1\ \mu H$, $R = 130\ \Omega$, $\phi = \pi/2$, $f_H = 2.3 \times 10^7$ Hz. This could add substantially to the risetime. However, doubling the peaker arms (lowering L_1) could substantially increase the high frequency cutoff.

It can also be shown that if the high frequency cutoff is large compared to the Marx/peaker resonant frequency and the optimum switch angle is used ($\phi = \pi/2$), the notch in the frequency spectrum occurs at

$$f_N \approx \frac{1}{2\pi\sqrt{LC}}$$

and the value of T at the notch is

$$T_N \doteq \frac{L_o - M}{L_o} \sqrt{\frac{C}{L}}\, R.$$

It is seen that only the mutual inductance affects the low frequency notch. With the mutual inductance coupling the two loops the peaking capacitance equation is modified by

$$C = \frac{L}{R^2} \left(\frac{L_o}{L_o - M} \right)^2$$

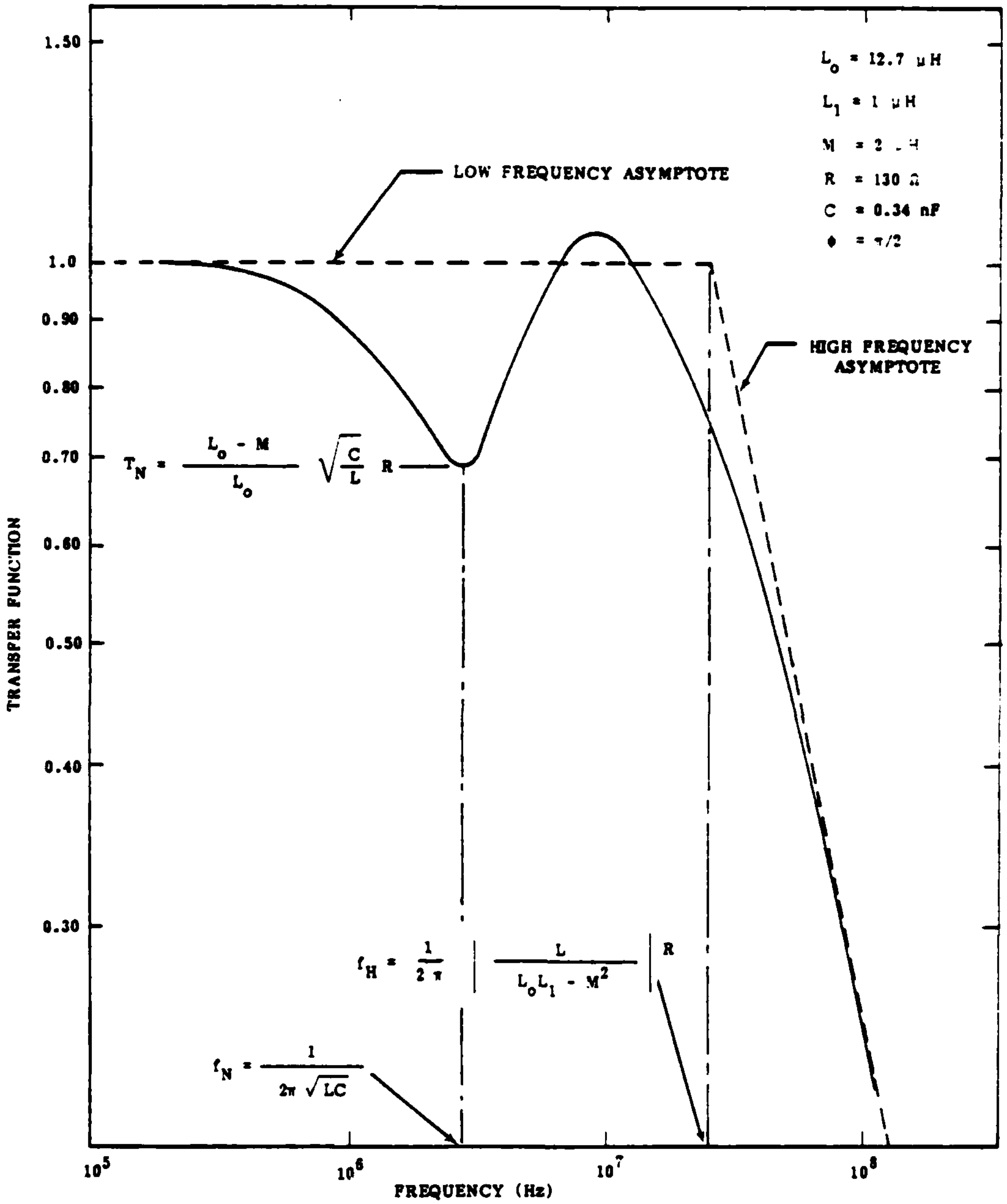


Figure F2. Magnitude of transfer function.

In effect, a larger peaking capacitance is required to match the Marx. For L_o =12.7 μH, M = 2 μH, C = 0.34 nF, L = 9.7 μH and R = 120 Ω, $T_N \simeq 0.65$ (-3.8 DB).

3. CONCLUSIONS

The basic conclusions of this simple analysis are:

- The self-inductance of the peaking capacitor is the dominant parameter affecting the high frequency cutoff.

- The mutual inductance between the Marx and output loop requires an increase in the peaking capacitances.

Both these effects should be reduced by increasing the number of peaking arms.

III. WAVE CONSIDERATIONS

Because of the distributed nature of peaking capacitors, the wave aspects of the pulser may be dominant at high frequencies. The wave effects broadly fall into two categories, diffraction effects and propagation effects. These will be discussed more fully below. Because of the geometry of the pulser it is difficult to do any wave analysis other than a TEM approximation. There is some doubt about the validity of this approximation as will be discussed below.

1. DIFFRACTION EFFECTS

Basically, diffraction includes all effects due to the mismatch between the wave field distribution and the conductors on which the wave is required to propagate. An example of this is the wave from the switch conic section propagating into the peaking capacitor structure. In general, because of the large fraction of energy propagating in the fringing fields of the pulser/simulator system, it is difficult to couple the switching wave into these fields. This is due to mismatch between the field distribution of the two waves. This mismatch leads to preferential radiation of the short wavelengths which leads to degradation of the risetime. In addition, discontinuities in the transmission line also scatter the high frequencies causing risetime degradation.

Most of these effects can only be determined practically by measurements. These would be done with low voltage fast rise pulses so that extensive high quality data can be taken. Qualitatively it is clear how to correct these problems. Various rearrangements of the peaker arms and the switch should improve the situation. Only measurements can tell for certain if the modifications will bring the magnitude of improvement that is needed.

2. PROPAGATION EFFECTS

Most of the wave-like analysis done on the TRESTLE system has in effect used the TEM approximation. This is true whether transmission line models or lumped element models were employed. Both models tacitly assume that the field distribution is unchanged and that only the spectrum of the wave is modified by the impedance of the propagating structure. This assumption should be carefully examined. In structures where there are large transverse dimensions such as TRESTLE, the impedance of the peaking capacitors can lead to the generation of non-TEM waves. This is because you cannot satisfy the E, H boundary conditions for a TEM wave and higher order modes must be present for a complete solution. In structures with resonances such as the peakers and the Marx, there are portions in the spectrum where the TEM wave may be cut off and attenuated.

Practically this means that any wave measurements of the peaking capacitor structure must be done in place. In this way the geometrical aspects will be correct. For this reason the wave measurements of a single peaking capacitor in a contrived experiment (such as in the 50 Ω geometry) probably do not give realistic results. For the propagation effects the low voltage fast wave testing of the structure is the only way to get quantitative results.

IV. PROPOSED TEST PROGRAM

In order to quantify the various causes of the waveform degradation, some experiments are required. These can be roughly grouped as wave propagation experiments and circuit experiments. A miscellaneous group would be improvements such as the peaking capacitor.

It would be very advantageous if the experiments could be used to validate a circuit model. This would allow more radical changes in geometry to be considered for the far term. An example of this would be the rearrangement of the Marx generator. The experiments and analysis should be designed to determine the sensitivity of the output to the components.

1. WAVE PROPAGATION TESTS

The overall purpose of the wave propagation tests would be to determine the response of the Marx/peaker system to a fast wave. Since the risetime of the field is determined by the ease with which the switching wave propagates this is the determining factor in the high frequency response of the system.

These tests should be relatively easy to perform since no major modification of the pulser is required. A fast rise (< 5 ns) generator would be required of sufficient amplitude to be seen on the E-field sensors either single shot or in the sampling mode. The detailed experiments are listed below.

a. Propagation through wave launcher--This test would replace the switch with an ideal wave launcher emanating from the focal point of the simulator wires. To do this a penetration would have to be made in the back of the gas enclosure but at low voltage this would be a minor operation. The tests would be performed with the peaking arms intact, completely shorted and alternate peaking elements shorted. To simulate the Marx coupling, the stages would have to be connected with wires which simulate the switch inductance. The field would be measured at the input to the generator and at the output of the generator.

This test would determine the best possible response of the generator structure and measure the degradation of the wave with the real capacitors. Alternate tests with the Marx shorted or not would test the effect of Marx/output loop coupling.

b. Propagation through switch cone--In this test the wave launcher would be removed and the switch installed. The tests of Section IV, 1 (a) would be repeated.

This experiment would identify the added degradation due to the conic wave launcher. Based on these tests the prospect of a radical design of the switch could be evaluated.

c. Miscellaneous tests--Depending on the outcome of the pulser propagation tests, experiments would be undertaken to determine if a better profile to the output transition would improve the waveform. This would be done with falsework between the pulser and the output transition. This test would be optional depending on the outcome of the pulser propagation tests.

From this experiment the possibility of a major change in pulser geometry would be evaulated.

2. CIRCUIT TESTS

The circuit tests would be done to determine the influence on the real waveform of circuit elements. The tests would be done at one-third to one-half full charge voltage so that radical changes can be made without the risk of a breakdown. In these tests the output switch current and E-field measurements would be made at the output of the switch and at the output of the generator.

a. Peaking capacitor tests--During these tests, the peaking capacitance would be varied by increasing the number of arms (up to eight arms total) and by shorting alternate sections. At each setting the firing angle would be varied and the influence on the spectrum noted.

The purpose of these tests would be to determine if by varying the peaking capacitance value and internal inductance a better match to the load could be achieved. Since the outer peaking arms have a different mutual inductance to the Marx loop than the inner ones they will carry a larger fraction of the charging current. This could lead to an effective mismatch. Putting more arms at the edges would test this effect.

By comparing the spectrum for the various cases, the optimum match for these capacitors can be achieved. The high frequency roll-off predicted by the simple analysis given above could also be checked.

b. Capacitive coupling tests--Because of the close proximity of the Marx generator to the peaking arms, the displacement current could cause some unbalance in the voltage distribution of the peaking arms. Although it is not easy to reduce the effect, it could be exaggerated to determine the sensitivity of the output to this parameter. This would be done by connecting water capacitors from the Marx grading rings to the peaker arms to enhance the coupling capacitance. If this experiment were used to normalize a computer model, changes in the Marx position could be evaluated without doing the experiment.

c. Switch jitter tests--If the high values of peaking capacitance are required to reduce the notch in the spectrum, the charging time will become longer since a reduction in Marx inductance is not practical. Switch jitter tests in the higher capacitance mode should be made to determine if there will be a synchronization problem between the two pulsers.

3. PEAKING CAPACITOR RESONANCE

In the BDM analysis of 1975 it was necessary to assume the peaking capacitance was 60% of the Maxwell stated value. Although tests at Maxwell at low and high frequencies indicate the design value was correct, a peaker element should be tested up to the highest significant frequency to determine the internal impedance. This would be done with a 606 PF element of the arm and not the whole arm. This test could determine the validity of BDM's 1975 analysis.

APPENDIX G

FINAL COMMENTS REGARDING RECOMMENDED ACTIONS FOR TRESTLE UPGRADE STUDY

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I. INTRODUCTION

This memorandum extends and reinforces the recommendations made in PATM 80-6, 5 September 1980, the initial report submitted to Mission Research Corporation under the present contract. In this memorandum, the recommendations made in the first memorandum are restated and extended; in the opinion of Pulsar Associates, Inc. execution of the actions recommended here will produce a marked improvement in the output pulse characteristics of the TRESTLE simulator.

Following the submission of the initial written work under this contract, a committee meeting was held in Albuquerque on 1 and 2 October 1980 at the offices of Mission Research Corporation. This meeting was attended by Mr. Ted Morelli of the AFWL, Ian Smith of ISI, John Shannon of Maxwell Laboratories, Tom Naff of Physics International, Jeremy Stein of EG&G, Dr. Dave Giri of LuTech and Walter Crewson of Pulsar Associates, Inc. The meeting was chaired by Jeremy Stein.

At this meeting, the initial written inputs were discussed and it was found that most of the committee members agreed that a reasonable measure to take is to increase the TRESTLE pulser peaking capacitance. It was generally agreed that this step will both reduce the pre-pulse, which is largely contributed by the switch capacitance as described in PATM 80-6, and will reduce the magnitude of the pulser "notch".

The relative importance of the mutual coupling between the peaking capacitors and Marx generator, which Pulsar believes is a strong contributor to the pulse shape distortions in TRESTLE, was debated at some length in the October meeting. Opinions differ on this point, and an experiment is clearly called for to investigate this effect. Pulsar is convinced that this coupling is quite important for the reasons given in Section III of PATM 80-6. More is said about this subject in Section II of the present memorandum.

Pulsar's recommendation that the TRESTLE output switches be converted to triggered switches was also widely discussed at the meeting and a variety of opinions were offered. The consensus seems to be that with the TRESTLE risetime already in the vicinity of 30 ns or more and with the maximum asynchronism between the switches in the neighborhood of 20 to 30 ns, very little would be gained by removing the switch asynchronism. Of course, it is possible that the asynchronism is a main contributor to the poor risetime. In this memorandum, we outline a recommended series of experiments that will identify the source of the risetime degradation and help to resolve this issue.

It was also suggested at the meeting that Pulsar discuss with Sandia Corporation the operation of the PBFA triggered three megavolt switches, and we have done this. A summary of these discussions is given in Section III of the present memorandum. Pulsar continues to recommend that the TRESTLE output switches be converted to triggered operation at the earliest opportunity.

In summary, the TRESTLE schedule since the inception of the present subcontract effort has relaxed considerably, making the pulser much more available for experimentation and modification than had been first anticipated. Consequently, Pulsar recommends that several experiments be done in the TRESTLE facility as soon as possible to identify unambiguously the source of the risetime and pulser "notch" problems and to clarify the issue of the relative importance of Marx-peaking capacitor mutual coupling. In addition, we reiterate our original recommendations that the peaking capacitance be increased by a factor of two, the Marx inductance be increased by a factor of two (thereby reducing the pre-pulse by a factor of two) and that the output switch be converted to uniform-field geometry and triggered operation. These changes should first be tested on the computer, as described below, using the test results obtained in TRESTLE to confirm the computer model. Also, the TRESTLE peaking capacitors should be tested in the laboratory to determine their wave propagation characteristics independently of TRESTLE. We believe these measures will clarify the more serious deficiencies in the TRESTLE pulser performance and will motivate a simple rational plan to correct the problems.

II. PEAKING CAPACITOR MUTUAL COUPLING

As discussed in Section III of PATM 80-6, the geometry of the TRESTLE pulser is unique in the EMP simulation world. Basically, the TRESTLE pulser is derived from the TORUS pulser hardware, with the peaking capacitor cone "unwrapped" from around the pulser and laid in a flat plane on one side of the Marx generator. This leads to an additional circuit complication which is absent from biconic pulsers with cylindrical symmetry such as the TORUS or HPD (HAG-IIC) pulsers. In the biconic pulser, in the limit of a large number of peaking capacitors, the outgoing wave launched by the closure of the output switch is unaffected by the contents of the cone. The cone can be filled with conducting material or even high permeability magnetic material without affecting the outgoing wave, since neither the electric or magnetic field associated with the outgoing wave penetrates the cone and affects the contents of the cone. The Marx generator and the outside world are truly de-coupled in this case. In the case of TRESTLE, this is clearly not true. The space between the peaking capacitors and Marx generator contains electric and magnetic fields which are generated not only by the Marx generator but also by the outgoing wave, since this space is not shielded geometrically from the rest of the simulator array.

We have performed a very simple laboratory experiment to illustrate this point. A Tektronix Type 109 fast-rising pulse generator was used to drive an open-wire transmission line and the transmitted pulse was observed with a fast oscilloscope (Tektronix Type 485). This set-up is sketched in Figure G1 (A). The transmitted pulse shape is shown in Figure G2 (A). In this case, the open-wire line was five feet long, with a round-trip clear time of 10 ns and the pulser and oscilloscope both rise in less than one ns. A two-foot section of the open-wire line was made as a three-conductor line with the third conductor suspended three quarters of an inch above the driven conductor and in the case of waveform G2 (A) not connected to the driven conductor. This is analogous to the situation in which the TRESTLE peaking capacitors are driven by a pulse generator with the peakers either covered with foil or left undisturbed and the transmitted pulse is observed downstream from the pulser with the Marx generator not connected in the circuit. The transmitted pulse of Figure G2 (A) is not a perfect step pulse but it departs by only about 10% from this pulse shape.

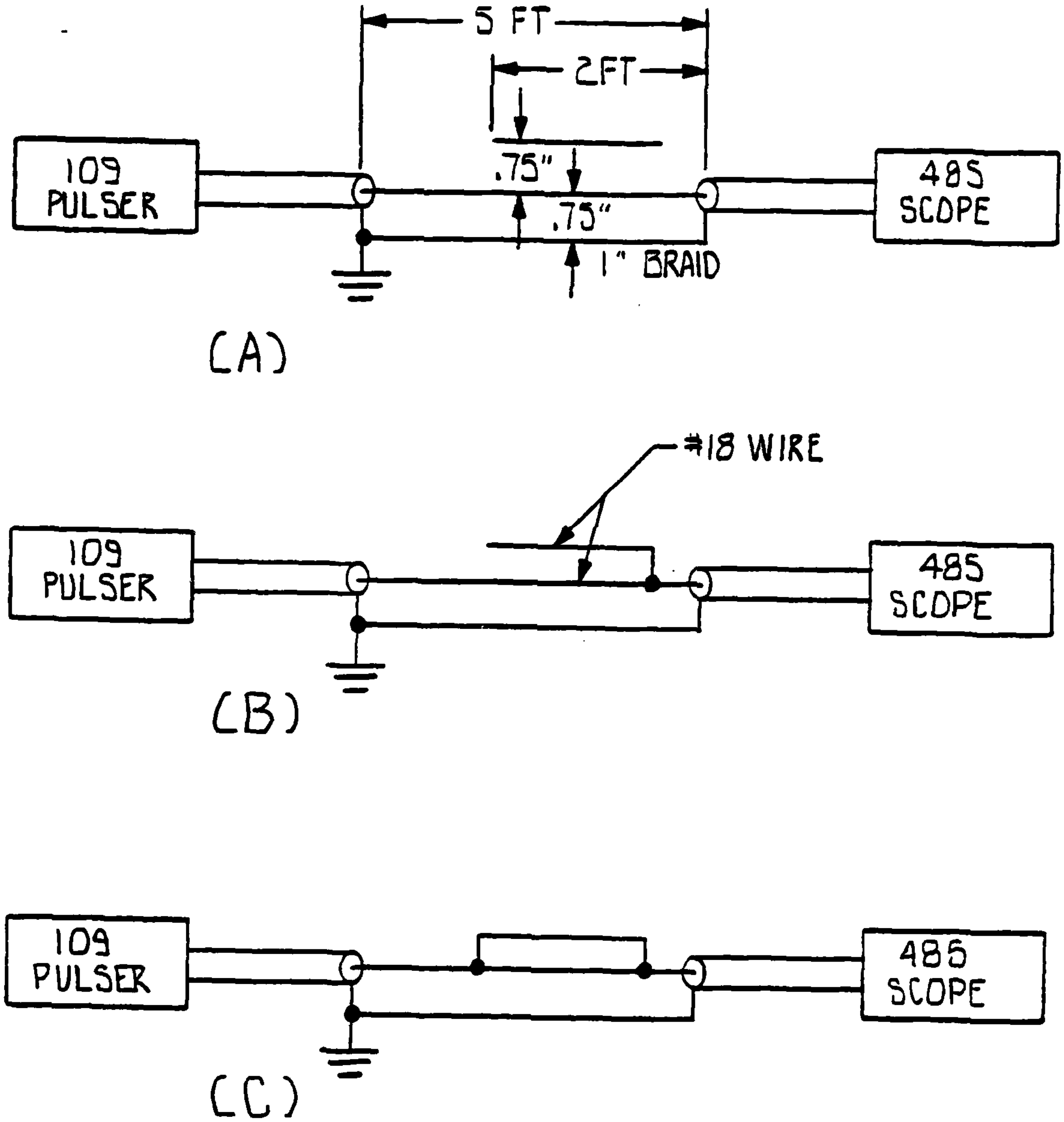

Figure G1. The experimental setups producing waveforms A, B, and C, which illustrate the effect on wave propagation of mutual coupling between the peaking capacitor plane and Marx generator in a TRESTLE pulser.

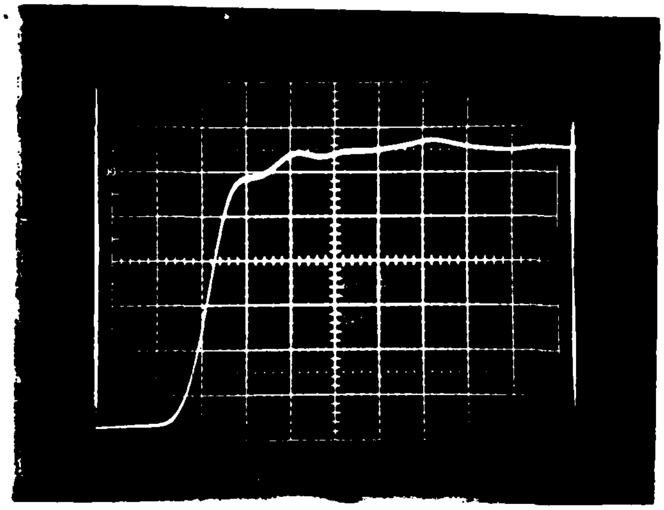

FIGURE G2 (A)
1 nS/div.
0.2 v/div.
TRANSMITTED PULSE FOR
SETUP OF FIGURE G1 (A).

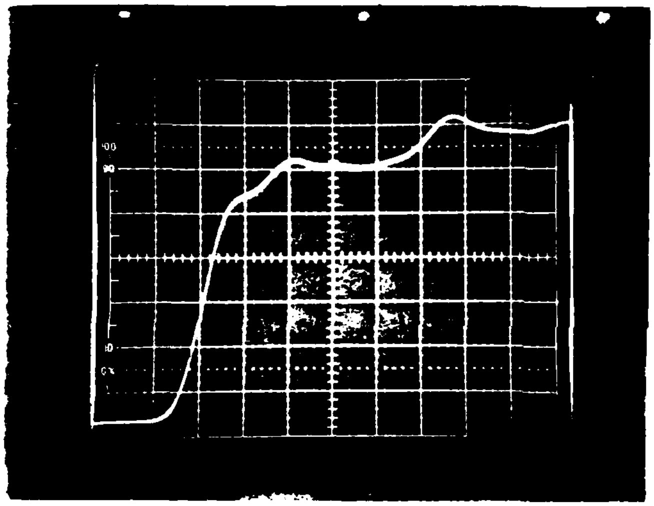

FIGURE G2 (B)
1 nS/div.
0.2 v/div.
TRANSMITTED PULSE FOR
SETUP OF FIGURE G1 (B).

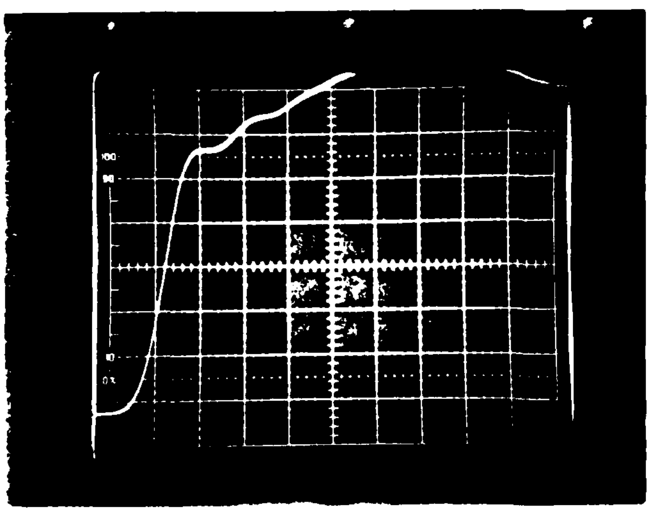

FIGURE G2 (C)
1 nS/div.
0.2 v/div.
TRANSMITTED PULSE FOR
SETUP OF FIGURE G1 (C).

Figure G2. Waveforms produced by the experimental setups shown in Figure G1.

Figure G1 (B) shows a case intermediate between no connection and complete connection of the third conductor. Clearly, the third conductor has a marked effect on the shape of the transmitted pulse. This case is shown mainly for the sake of completeness since it will not in general arise in TRESTLE. The Marx generator is either fully erected or it is not erected and the pulser does not fire. However, it does indicate the importance of attaching even a relatively small capacitance to the output end of the pulser. In the case of TRESTLE, this would be represented by the stray capacitance of the large metal "transition" box connected at the high voltage end of the Marx generator which contains the trigger generator components. This box probably has a significant effect on the pulser risetime and waveform oscillations.

Figure G2 (C) shows the transmitted pulse with both ends of the third conductor attached to the driven conductor. This case is analogous to the situation faced by the pulse generated by the TRESTLE main switch as it propagates out toward the working volume with the Marx generator fully erected. As can be seen, the initial part of the rise seems the same as in Figure G2 (A), but the rise is immediately followed by a large upward excursion in transmitted voltage. We interpret this effect in the same way as the discussion of Section III, PATM 80-6 indicates. The transmitted pulse is initially undisturbed by the added conductor to at least a first order of approximation since no magnetic field can link the short-circuited loop formed between the driven wire and the added conductor. This overall geometry does constitute a transmission line with lower impedance and so slightly more pulse voltage (about ten percent for the case here) is transmitted from the high impedance open-wire line to the 50 ohm oscilloscope. However, in a time governed by the L/R time constant of this shorted loop, circulating current can build up in the loop, allowing flux to link the area of the loop and gradually reducing still further the net series impedance of this section of the transmission line. In effect, the full "fringing field" of this section of line is initially prohibited from being established by the short-circuited loop. As this field is set up, the pulse transmitted trails upward, eventually exceeding the initial amplitude by about 25 percent as shown in Figure G2 (C). When this effect occurs in the TRESTLE pulser, the additional magnetic and electric stored energy in the fringing field must be provided by the Marx generator and peaking capacitor. We believe this contributes substantially to the "notch" following the initial rise of the pulse. It also helps to explain why the "ideal" peaking capacitor value which was used in design of the TRESTLE pulser is not large enough for the real case. Much of this extra energy is drawn from the peaking capacitors since these are a lower-inductance energy source than the Marx. This presents a lower effective load impedance to the peaking capacitors.

Since the TRESTLE user schedule has relaxed, Pulsar recommends that this type of experiment be conducted using the actual TRESTLE hardware. An experiment which will simultaneously address the issues of risetime degradation and the mutual coupling problem is outlined as follows.

1. Obtain a pulse generator with 5 to 10 kV amplitude to overcome any contact resistance effects that might cause trouble if pulsers of a few hundred volts are used. The pulser risetime should be one nanosecond or less. A series sharpening gap can be added to one of the existing TRESTLE trigger generators to obtain the required pulse.

2. Connect this pulser to the output switch cone by removing the ground-end cover plate from one of the output switches and connecting a coaxial cable to the output switch main electrode.

3. Fire this pulser through the TRESTLE pulser and observe the transmitted pulse at several locations on the ground plane downstream of the pulser.

4. Cover the peaking capacitors with aluminum foil and repeat this test. This will identify the role of peaking capacitor inductance and resonance in the risetime degradation.

5. Short-circuit the Marx generator stages by connecting a length of copper braid across all of the grading rings as suggested by Ian Smith. This can provide a reasonable simulation of the erected Marx. Repeat the transmitted pulse test for this case both with and without the peaking capacitors covered in foil.

6. Add two more peaking capacitors to the pulser assembly and repeat the transmitted pulse measurement.

7. Increase the number of peaking capacitors to a total of eight arms and repeat the measurement. Position the arms both in the plane of the Marx generator and below the Marx generator to determine the importance of equalizing the peaking capacitor currents.

By analyzing this transmitted pulse data a relatively simple circuit model of the TRESTLE pulser can be quickly constructed, including the effects of peaking capacitor resonance and mutual coupling between peaking arms and Marx generator. This model can be exercised using the computer to examine the effect of adding inductance to the Marx generator and varying the firing angle of the main switch. These alterations are more difficult when using the full TRESTLE output voltage than is the low-level transmitted pulse test, and the computer should be brought in at this point to examine the advisability of making major alternations in the TRESTLE pulser and to examine which changes are likely to be most beneficial.

Prior to the transmitted pulse test outlined above, the actual TRESTLE pulse should be measured on the ground plane of one of the wave launchers at several locations downstream of the output switch, to provide a data base comparison with the computer results and to give a preliminary indication of how rapidly the risetime degrades as the pulse transits the pulser assembly and travels toward the working volume.

III. TRIGGERED OUTPUT SWITCH

In January of 1981, we visited Tom Martin's group at Sandia Corporation to discuss the operation of the triggered output switch in PBFA. The exact mode of operation of this switch is still a topic of discussion among members of this group, and the speculation is that either the switch is triggered directly by the photon beam generated by the trigger pin or it is operating in a more conventional "trigatron" mode in which the changing potential of the trigger pin launches simultaneously a main streamer that bridges the entire switch gap and a minor streamer that bridges the gap between the trigger pin and the electrode in which it is embedded. Pulsar has had considerable experience with lower voltage trigatrons operating in this "standard" mode and has found that jitters of one nanosecond (as are observed at Sandia) cannot be obtained in this way.

The Sandia group originally had thought that the switch operated in the over-volted mode described in Section IV of PATM 80-6. However, they are less sure of this now since the self-breakdown voltage measurements have been considerably refined and it appears that the switch is in fact being triggered at a voltage below its self-breakdown voltage. The fact remains that whatever the mechanism at work here, the switch does operate and on each shot at PBFA, 32 of these switches are triggered with time jitters on the order of one nanosecond. The most common switch fault is an early firing by ten or fifteen nanoseconds, counted by Sandia as a "pre-fire". This fault mode suggests that perhaps the switches are in fact being pulse-charged above their self fire voltage and are being triggered by the sudden application of ultraviolet light and the consequent release of photelectrons as described in Pulsar's earlier memorandum.

In any case, the performance of this switch is markedly superior to the performance of the existing TRESTLE output switches. At Sandia, this switch operates at 3 million volts and carries currents in the neighborhood of 200,000 amperes. At TRESTLE, the output switch operates at 4 to 5 million volts with currents of 30,000 to 40,000 amperes. This much lower peak current should materially increase the useful operating life of the switch. Since the ground electrode of the TRESTLE output switch is easily removed, the idea is easy to try on one of the two TRESTLE pulsers, and we recommend it be tried at the earliest possible time. To fully apply this triggered switch system to both TRESTLE pulsers, one of the two trigger generators would need to be isolated from ground and installed at the high voltage end of the output switch, since the best triggering performance is obtained when the trigger pin is located in the positive electrode of the output switch. For a trial, however, a grounded pulse generator can be used to trigger one of the two output switches with the TRESTLE pulser operated in both polarities to obtain comparative jitter data. This and the ground-plane pulse measurements are the only high voltage experiments Pulsar recommends for the near term at TRESTLE. Other high voltage experiments involving increased numbers of peaking capacitors and increases in the Marx generator inductance should only be carried out after the transmitted pulse measurements described in Section II and the brief computer modeling exercises which follow those measurements.

IV. PEAKING CAPACITOR CHARACTERIZATION

The questions of peaking capacitor inductance and resonant frequencies have been raised several times during the present effort, and existing measurements (made several years ago) provide unclear answers. Pulsar recommends that one TRESTLE peaking capacitor arm be installed as the driven electrode in a stripline geometry and its pulse transmission and reflection behavior be measured. This experiment should be done in the laboratory, using a generator of several kV amplitude in addition to a lower-level pulser to look for nonlinear response effects (internal capacitor contact arcing, etc.). The experiment will yield an accurate equivalent circuit model for the peaking capacitor that can be compared to the one developed from the measurements made at TRESTLE and can be used in the computer modeling effort which precedes major hardware alterations in TRESTLE.

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